



ZAIN ALI

Developing the through-transmission technique in pulsed
thermography for material characterisation

FACULTY OF ENGINEERING AND APPLIED SCIENCES
Centre for Digital and Design Engineering

PhD

Academic Year: 2022 - 2025

Supervisor: Dr. Pavan Addepalli
Associate Supervisor: Prof. Yifan Zhao
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Abstract

Pulsed Thermography (PT) is a reliable, non-contact, and non-intrusive non-destructive testing (NDT) technique for assessing the structural health of materials. Based on the relative positioning of the thermal excitation source and the infrared radiometer, measurements can be conducted in either reflection or transmission mode. While reflection mode is widely adopted due to its single-sided accessibility, transmission mode offers superior lateral resolution but remains limited in use due to the lack of reliable depth quantification methods. In the context of thermal diffusivity evaluation, the transmission mode has demonstrated greater reliability; however, the existing literature lacks a deterministic approach to systematically assess this in laboratory settings. This research investigates the current state-of-the-art in through-transmission thermography and identifies key knowledge gaps. A transparent and repeatable methodology is developed to evaluate thermal diffusivity using both finite element models (FEM) and controlled laboratory experiments. The FEM is also used to assess the temporal behaviour of a sample containing subsurface defects, and a physical sample is fabricated to validate the simulation results. A novel method for defect depth quantification is then proposed by establishing a relationship with the Fourier number. This approach demonstrated a 63% improvement in depth estimation accuracy (from a 29.3% measurement error to 10.75%) compared to the Log Second Derivative (LSD) method derived from thermographic signal reconstruction (TSR) in the simulation environment across all defect sizes and depths. Additionally, the technique shows potential for estimating impact damage in carbon fibre-reinforced polymer (CFRP) samples subjected to varying impact energy levels. By addressing the challenges of thermal property measurement and depth quantification within the transmission mode, this thesis provides a foundation for improved material characterisation and supports renewed research interest in through-transmission pulsed thermography.

Keywords: infrared thermography; pulsed thermography; through–transmission; thermal diffusivity; defect depth quantification; finite element analysis; non-destructive testing

List of Publications

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- Ali, Z.; Addepalli, S.; Zhao, Y. *Effective Thermal Diffusivity Measurement Using Through-transmission Pulsed Thermography: Extending the Current Practice by Incorporating Multi-Parameter Optimisation*. *Sensors* **2025**, *25*, 1139. <https://doi.org/10.3390/s25041139>
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- Ali, Z.; Addepalli, S.; Zhao, Y. *A theoretical investigation into material characterisation using pulsed thermography in the reflection and transmission modes*, *Proc. SPIE* 12536, Thermosense: Thermal Infrared Applications XLV, 1253609 (12 June 2023); <https://doi.org/10.1117/12.2665178>
- Ali Z, Peng S, Addepalli S, Zhao Y. (2024) *Infrared thermography- a study into its current capabilities and future prospects*. In: 12th International Conference on Through-life Engineering Services – TESConf2024, 6-7 June 2024, Cranfield, UK

Datasets

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“Indeed, in the creation of the heavens and the earth and the alternation of the night and the day are signs for those of understanding.” (Surah Al-Imran, 3:190)

I begin by praising Allah (SWT), the Lord of the Worlds, and sending peace and blessings upon His final Messenger, Prophet Muhammad (peace be upon him), who brought to humanity the gift of Islam, a light and guidance for all those who seek the truth. This Qur'anic verse reminds us that the natural world is full of divine signs, encouraging reflection and understanding. In my own journey, I am humbled to have been granted the opportunity to study one of these signs through the lens of science. My research in infrared thermography, which lies within the electromagnetic spectrum, explores aspects of light and heat, elements that are not only physical phenomena, but also spiritually significant. Engaging with the study of light, even in its limited worldly form, feels like a small window into understanding the majesty of His attributes. For this reason, this research holds a personal and spiritual significance, as it serves as both a scientific exploration and a form of contemplation on one of Allah's characteristics.

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mine. I would also like to thank my mother for making the incredibly difficult decision to come here and support us, while my father remained in the UAE due to work commitments. Their love and devotion to each other must have made that decision especially painful, and it is a sacrifice I know I can never fully repay.

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Finally, I would also like to take a moment to dedicate this work to those around the world whose lives have been shaped or limited by circumstances beyond their control. Their quiet strength and perseverance in the face of adversity have been a powerful reminder of the privileges I often take for granted. The opportunity to pursue education and personal growth is one not afforded to all, and I carry that awareness with deep gratitude. This thesis is offered in honour of those who may never have had the chance to follow their dreams, yet whose untold potential might have made a lasting and positive impact on the world.

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List of Abbreviations

ACF	Autocorrelation Function
AI	Artificial Intelligence
AM	Additive Manufacturing
CFRP	Carbon Fiber Reinforced Polymer
CNTT	Carbon Nanotube-based Thermography
CT	Computed Tomography
CV	Coefficient of Variation
DCCA	Diffusion-Compensated Correlation Analysis
DoE	Design of Experiments
ERCM	Electrical Resistance Change Method
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FMT	Frequency Modulated Thermography
FPA	Focal Plane Array
IoT	Internet of Things
IRT	Infrared Thermography
LFA	Laser Flash Apparatus
LIT	Lock-in Thermography
LLT	Laser-Line Thermography
LPT	Long Pulse Thermography
LSD	Log Second Derivative
LST	Laser-Spot Thermography
MT	Metal-based Thermography
MWT	Microwave Thermography
NDT	Non-destructive Testing
NETD	Noise Equivalent Temperature Difference
NLSF	New Least Squares Fitting
NUST	Nonlinear Ultrasonic Stimulated Thermography
PCT	Principal Component Thermography
PEC	Pulsed Eddy Current thermography
PPT	Pulsed Phased Thermography

PT	Pulsed Thermography
RB	Reflection Back
RF	Reflection Front
ROI	Region of Interest
SHT	Step Heating Thermography
SLR	Systematic Literature Review
SMA-T	Shape Memory Alloy-based Thermography
SNR	Signal-to-noise ratio
TB	Transmission Back
TF	Transmission Front
TSR	Thermographic Signal Reconstruction
TWR	Thermal Wave Radar Analysis
UST	Ultrasonic Stimulated Thermography
UT	Ultrasonic Testing

1 Introduction

Infrared Thermography (IRT) is a non-contact, non-destructive evaluation technique (NDT) that detects and interprets the thermal radiation emitted by objects in the infrared spectrum. Widely used in fields ranging from industrial inspection to biomedical diagnostics, IRT provides valuable insights into surface and subsurface phenomena based on thermal behaviour. Among the various active thermography methods developed under the IRT umbrella, Pulsed Thermography (PT) stands out for its simplicity, speed, and versatility in characterising material properties. Current literature indicates that reflection mode in PT has received more attention than transmission mode. This thesis focuses on exploring the capabilities of through-transmission PT for material characterisation, with particular emphasis on its application in estimating thermal diffusivity. The aim of this work is to advance the use of through-transmission PT for both material and defect characterisation. The remainder of this introduction outlines the historical development of the technique, its working principles, the motivation for this research, the aims and objectives, the thesis format, and structure.

Since its discovery in 1800 by Sir William Herschel [1], infrared radiation has found diverse applications across multiple industries in the form of IRT for the thermal assessment of materials. Although progress in infrared technology was initially slow, with nearly 40 years passing before John Herschel produced the world's first thermogram and another 40 years before the invention of the bolometer, significant advancements were made throughout the late 19th and 20th centuries. Key milestones in this progression are illustrated in Figure 1-1. In recent years, IRT has firmly established itself as a practical and reliable NDT technique. Further statistics reflecting the growth and adoption of IRT in both academic research and industrial applications are provided in 6.2Appendix B of this thesis.

IRT inspections can be conducted in either the active or passive modes. The active mode requires external thermal stimulation to the object under examination whereas the passive mode observes the inherent thermal characteristics of the

object. The external thermal excitation can be achieved via several means (Details of which can be found in Table 2-1). With the wide range of applications and excitation methods, a comprehensive analysis of all the active thermography types cannot be conducted within the timeframe of this PhD thesis. Therefore, the sole focus of this thesis would be in the area of Pulsed Thermography (PT). A similar analysis to 6.2Appendix B was conducted for PT, however details of PT's growth in the commercial sphere was difficult to obtain due to the lack of available studies. Therefore, only an academic landscape has provided in 6.2Appendix C6.2Appendix C. Before exploring the details of IRT, it is important to first understand the fundamental principles of infrared radiation. The following paragraphs are intended to provide the necessary background and context to support the technical discussion that follows.

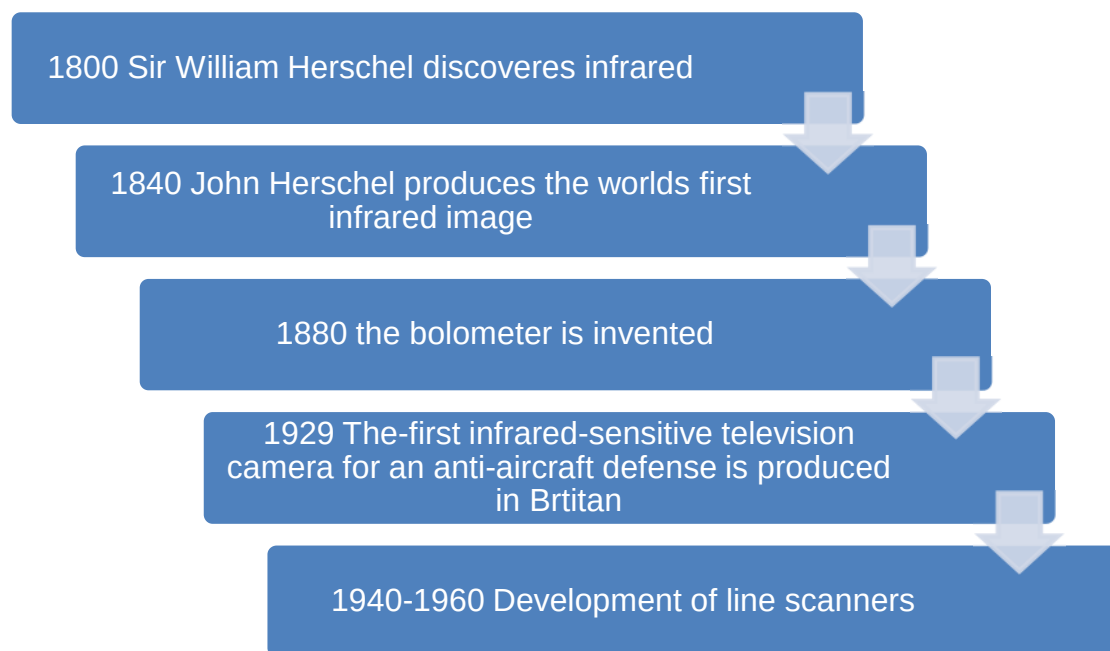


Figure 1-1 A brief timeline of the major developments in infrared thermography from the 19th to the 20th century

Electromagnetic waves are a form of energy propagation that travel through space as oscillating electric and magnetic fields, capable of transmitting energy across the universe without the need for a medium. They are generated when an electric field couples with a magnetic field, with both fields being perpendicular to each other and to the direction of travel. The size of these waves varies (See

Figure 1-2), and the wavelength segment between 700 nm and 1 mm is known as the infrared spectrum.

The speed of an electromagnetic wave in a vacuum is the speed of light i.e., $3 \times 10^8 \text{ m/s}$. Each wave carries energy which is dependent on its frequency and wavelength. The higher the frequency the greater the energy. The energy is measured in electron volts (eV) and the energy of a single photon is governed by the equation below:

$$E = h\nu \text{ or } E = \frac{hc}{\lambda} \quad (1-1)$$

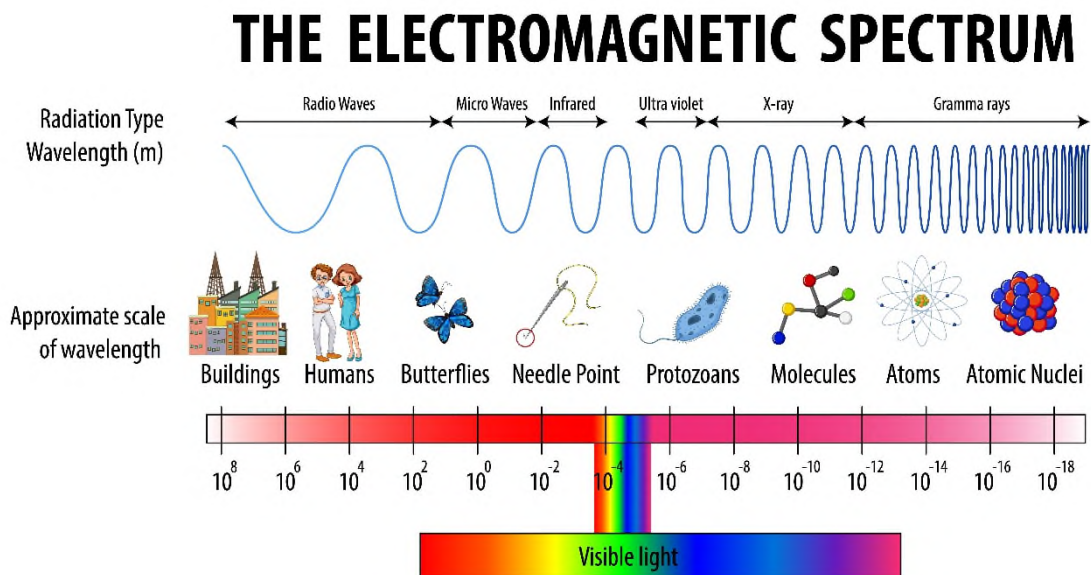


**Figure 1-2 The electromagnetic spectrum [measurement unit is meters (m)] [2]
(Image designed by Freepik)**

where h is Planck's constant ($6.626 \times 10^{-34} \text{ J}\cdot\text{s}$), ν is the frequency (Hz), c is the speed of light ($3 \times 10^8 \text{ m/s}$), and λ is the wavelength (m).

As a wave approaches an object, it is either reflected, transmitted, or absorbed. Reflection occurs when the wave bounces off the material's surface, transmission when it passes through the material, and absorption when the material takes in the wave's energy, increasing its internal energy. At a subatomic level, absorption involves electrons moving from their ground state to an excited state due to the

energy carried by incoming photons. For this to occur, the photons must match a specific frequency that the material can absorb, known as the resonant frequency [3]. Eventually, the electron returns to its ground state to restore equilibrium, releasing energy in the form of a photon. When this emitted photon falls within the infrared range of the electromagnetic spectrum, it can be detected by IRT systems. This principle forms the foundation of infrared thermography, where infrared detectors capture emitted radiation to analyse the thermal characteristics of a material.

1.1 Research Motivation

Figure 1-3 presents a SWOT analysis highlighting the current strengths, weaknesses, opportunities, and threats related to thermal diffusivity estimation using through-transmission thermography [4–10].

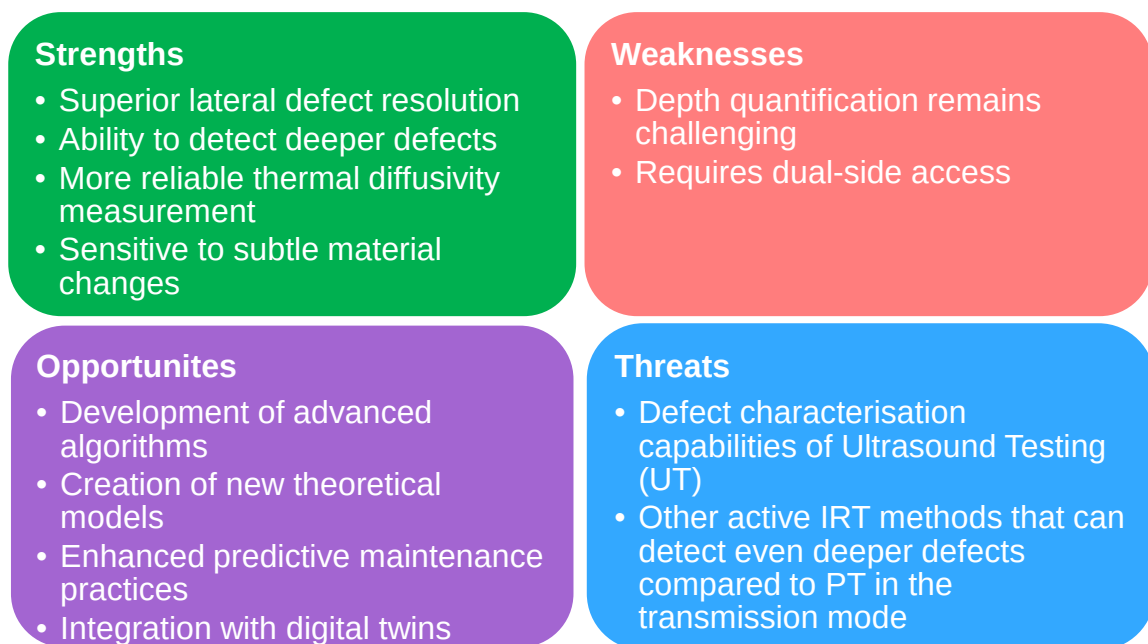


Figure 1-3 SWOT analysis for through-transmission pulsed thermography

It will become apparent in the following chapters that most pulsed thermographic research is focused on the reflection mode. This is primarily due to the fact that most research has concentrated on defect detection rather than the evaluation of thermal properties. Moreover, in many practical applications, access to the rear surface of the specimen is often limited or impossible, thereby making one-sided

testing a more viable and attractive approach. Existing literature has shown that the reflection mode is less reliable for thermal material property evaluation such as thermal diffusivity when compared to the transmission mode [11]. Thermal diffusivity evaluation is essential for understanding a material's structural integrity. In safety-critical industries, detecting anomalies in thermal behaviour can serve as an early indicator of defects or degradation. This early detection enables informed decision-making on maintenance, repairs, or replacement, ultimately enhancing safety and performance reliability. Accurate measurement of thermal diffusivity provides the quantitative foundation necessary to detect subtle changes in a material's thermal response, enabling predictive maintenance strategies and reducing the risk of unexpected failures. This precision not only supports rigorous quality control but also enhances the longevity and resilience of components in demanding operational environments.

Despite the importance of thermal diffusivity in assessing material integrity, there is currently no standardised approach that verifies the accuracy of its measurements by integrating both theoretical and experimental perspectives. In the limited body of research focused on through-transmission thermography, existing literature lacks a comprehensive analysis of the reliability and consistency of thermal diffusivity measurements. A systematic framework that bridges theoretical models with experimental validation is still missing, leaving a critical gap in ensuring measurement accuracy and repeatability. Current methods are limited to expensive commercial instruments that require temperature-controlled chambers and multiple calibrations. Moreover, the method used to evaluate thermal diffusivity was developed over six decades ago and has seen minimum improvements since [12]. In terms of defect detection, the transmission mode exhibits superior lateral defect resolution in comparison with the reflection mode. However, the depth quantification is a challenge in this mode. On the other hand, the reflection mode can quantify defect depth but is limited to shallow subsurface defects (further details in Chapters 2–4). This is why a major portion of existing literature shows pulsed thermographic research being undertaken exclusively in the reflection mode. If reliable depth quantification can be achieved in through-transmission pulsed thermography, it will significantly

expand the technique's applicability, enabling precise localisation and characterisation of subsurface defects, and making it a more viable solution for complex, multilayered, or thick-sectioned materials commonly found in aerospace, energy, and advanced manufacturing sectors.

The vital importance of thermal diffusivity measurement [13] and the lack of theoretical and experimental methodologies to evaluate this quantity is the primary motivation that has driven this research. This research seeks to address this critical gap by developing theoretical and experimental models that not only provide a systematic framework (both theoretical and experimental) for thermal diffusivity measurement, but also to extend that framework to enhance the current defect characterisation capabilities of through-transmission thermography. Addressing these gaps, particularly those highlighted in the weaknesses section of Figure 1-3, can shift the focus beyond lateral resolution and basic material characterisation, enabling more comprehensive, depth-resolved thermal analysis that aligns with Industry 4.0 objectives such as real-time monitoring, predictive maintenance, and the integration of digital twins for intelligent asset management.

1.2 Research Aim and Objectives

The aim of this research is to critically evaluate thermal material properties using through-transmission pulsed thermography and to extend its capabilities through the enhancement of depth quantification, enabling comprehensive characterisation of both material and defects. Figure 1-4 shows the detailed methodology used to achieve the five objectives stated below:

1. Identify the current state-of-the-art in pulsed through-transmission thermographic measurements by conducting a systematic literature review.
2. Determine the current capabilities of through-transmission thermography by creating FEM model and conducting experiments following a full factorial Design of Experiments (DoE)

3. Extend the FEM to include subsurface defects and create a physical calibration sample containing subsurface defects to validate the FEM experimentally
4. Propose a novel solution not available in current literature to quantify defect depths in the transmission mode and compare the proposed method with the Log Second Derivative method (LSD) in the reflection mode.
5. Test the proposed method on uncalibrated defects such as impact damage in CFRPs and assess its accuracy in estimating the impact damage.

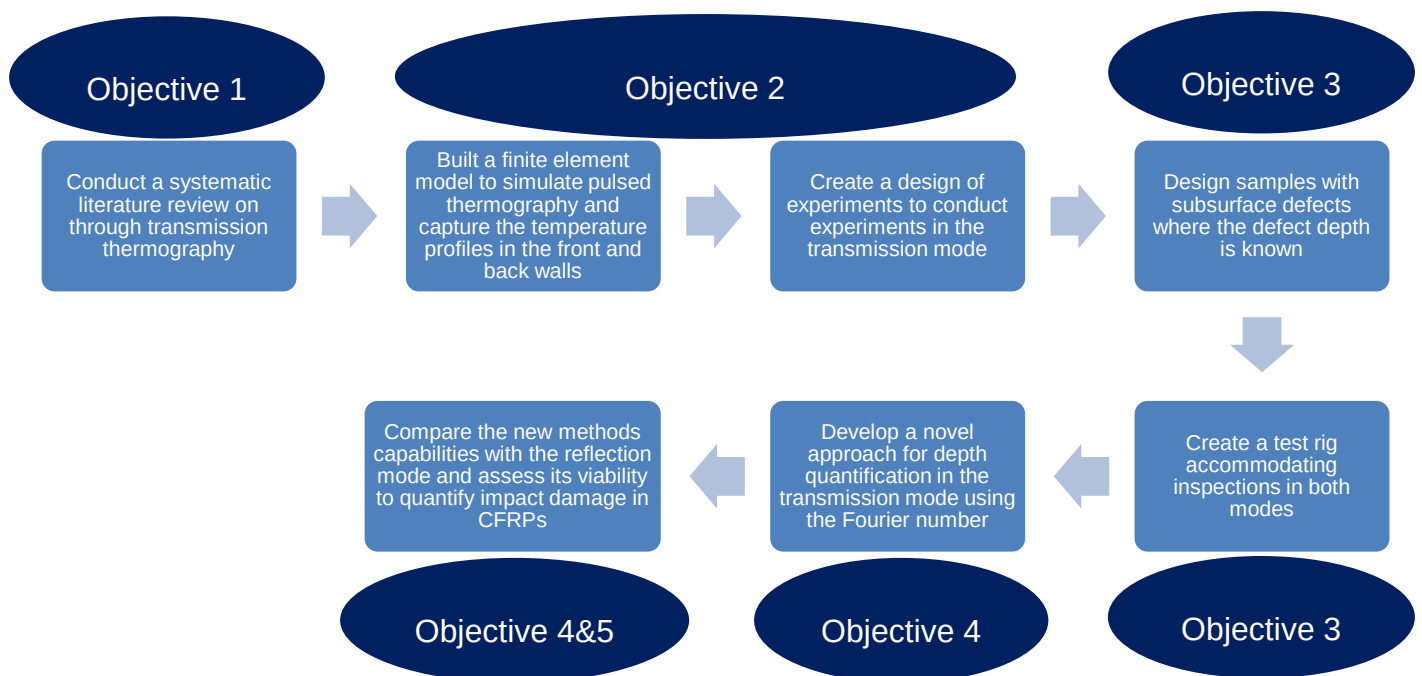


Figure 1-4 Methodological steps taken to achieve the stated objectives

1.3 Thesis format and structure

Traditional theses follow the monograph format which begins with a general introduction to the topic, followed by a comprehensive literature review that generally provides a theoretical background to the topic, methods and materials, results, discussion, and finally a conclusion. What is important to note here is that each chapter is unique in terms of the content that it contains, and all the chapters combine to provide an overall story with regards to the research topic.

Paper format theses are slightly different in this regard that each chapter has its own introduction, theoretical background, methods and materials, results, discussion, and conclusion. This leads to some of the content especially in the introduction and background section being repeated due to each chapter being a paper that has either been published or submitted for publication. However, a paper format thesis has a certain advantage over the traditional format in terms of peer review, and that it provides the students with opportunities to gain experience on how to present their work in a concise format aiding in their personal and professional development. For these reasons, the thesis has been written in this paper-based format. While some sections may overlap, each chapter contributes uniquely, providing a structured flow to the overall thesis that aligns with its aims and objectives. Figure 1-5 illustrates the alignment between the research objectives and the papers in which they are addressed. Figure 1-6 presents the key takeaways from each chapter. Chapter 2 identifies several research gaps within the context of pulsed thermography, which are addressed in the subsequent chapters.

The first objective was to identify the current knowledge gap, for which a systematic literature review was conducted [14]. A systematic review is preferred over a general review because it follows a rigorous and transparent methodology that minimises bias and ensures comprehensive coverage of literature relevant to a specific research question, in this case, the current limitations of through-transmission thermography. Moreover, it lays the foundation for the remainder of this research, which aims to address the identified gaps by proposing a structured methodology for measuring thermal diffusivity and validating the approach both theoretically through finite element modelling and experimentally in a laboratory environment [13]. Building on the validated theoretical model, the next objective was to address the most critical gap: depth quantification in through-transmission thermography [8]. This involved designing a sample with subsurface air gaps at known depths to enable a comparative analysis between finite element simulations and laboratory experiments. At the time of submitting this thesis, the systematic literature review (Chapter 2) [14] and the methodology paper (Chapter

3) [13] have been published, and the fourth chapter that deals with the depth quantification, has been submitted for publication.

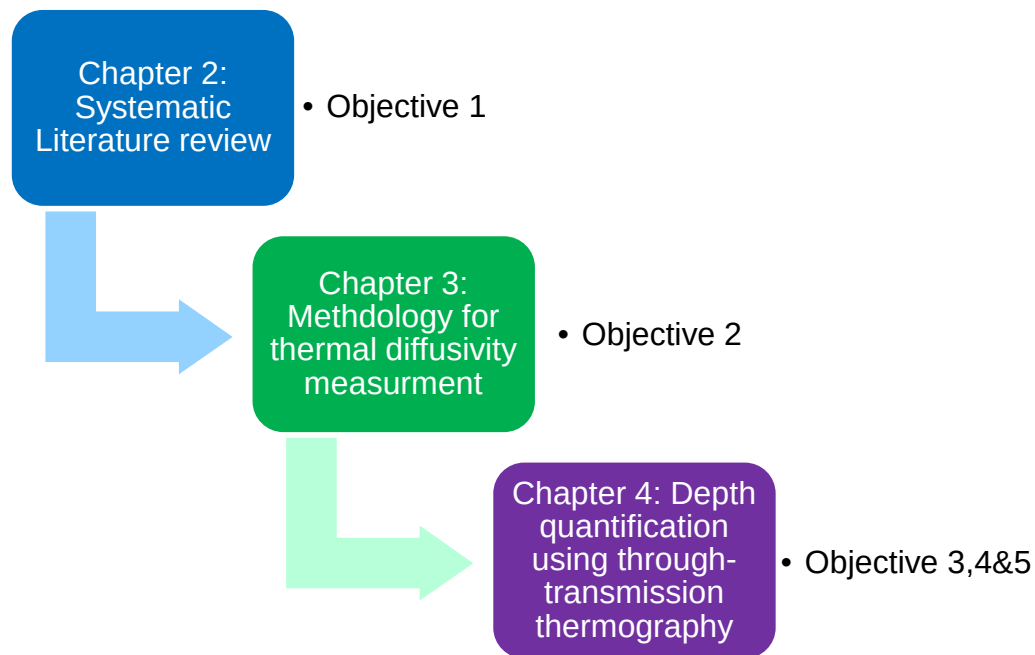


Figure 1-5 Diagram explaining how each is linked to one or more objective

Chapter 2	Chapter 3	Chapter 4
<ul style="list-style-type: none"> • Limited theoretical models exist for pulsed thermography in the transmission mode. (Addressed in Chapter 3) • No standardised approach exists to assess thermal diffusivity using through-transmission pulsed thermography in laboratory environments. (Addressed in Chapter 3) • No physical calibration samples with airgaps at known depths exist in the current body of literature. (Addressed in Chapter 4) • Depth quantification is a challenge for pulsed thermography in the transmission mode. (Addressed in Chapter 4) 	<ul style="list-style-type: none"> • For the FEM, Parker's method delivers more accurate results for thermal diffusivity in the transmission mode at higher sample thickness, whereas NLSF exhibits minimal sensitivity to thickness variations. • NLSF offers more precise estimates for thermal diffusivity especially at lower thicknesses and higher energy levels compared to Parker in the laboratory experiments. 	<ul style="list-style-type: none"> • As the defect depth increases, the effective thermal diffusivity decreases till the depth is half that of the sample's overall thickness. Beyond this the effective thermal diffusivity starts to increase. • As the defect moves closer to the backwall, the first derivative peaks of the reflection mode move closer to their transmission counterparts. • A linear relationship can be established between the Fourier number and defect depth which can then be used to predict the depth of the defect in the transmission mode

Figure 1-6 Key takeaways from each chapter

The rest of this thesis is organised as follows

1. Chapter 2 highlights the existing knowledge gap in through-transmission thermography and outlines the direction and rationale for the research undertaken in this study.
2. Chapter 3 presents a systematic framework for thermal diffusivity measurement by refining the existing methodology and benchmarking it against current standard approaches.
3. Chapter 4 builds on the proposed methodology developed in chapter 3 by incorporating subsurface defects and proposes a novel solution to quantify defect depth.
4. Chapter 5 provides an overall discussion of the previous three chapters.
5. Chapter 6 concludes the thesis by summarising the key findings and highlighting the original contributions this research makes to the field as well as an outline of future works.

2 Systematic Literature Review

Thermal Material Property Evaluation Using Through-transmission Thermography: A Systematic Review of the Current State-of-the-Art

Published as Ali, Z.; Addepalli, S.; Zhao, Y. Thermal Material Property Evaluation Using through Transmission Thermography: A Systematic Review of the Current State-of-the-Art. Appl. Sci. 2024, 14(15), 6791; <https://doi.org/10.3390/app14156791>

Abstract

Determining thermal material properties such as thermal diffusivity can provide valuable insights into a material's thermal characteristics. A well-established method for this purpose is flash thermography using Parker's half-rise equation. It assumes one-dimensional heat transfer for thermal diffusivity estimation through the thickness of the material. However, research evidence suggests that the technique has not developed as much as the reflection mode over the last decade. This systematic review explores the current state-of-the-art in through-transmission thermography. The methodology adopted for this review is the SALSA framework that seeks to Search, Appraise, Synthesise, and Analyse a selected list of papers. It covers the fundamental physics behind the technique, the advantages/limitations it has, and the current state-of-the-art. Additionally, based on the Population, Intervention, Comparison, Outcome, and Context (PICOC) framework, a specific set of inclusion and exclusion criteria was determined. This resulted in a final list of 81 journal/conference papers selected for this study. These papers were analysed both quantitatively and qualitatively to identify and address the current knowledge gap hindering the further development of through-transmission thermography. The findings from the review outline the current knowledge gap in through-transmission thermography and the challenges hindering the development of the technique, such as depth quantification in pulsed thermography and the lack of a standardised procedure for conducting measurements in the transmission mode. Overcoming some of

these obstacles can pave the way for further development of this method to aid in material characterisation.

Keywords

systematic review; 1D heat transfer; through-transmission thermography; material defect characterisation; non-destructive testing

2.1 Introduction

The first industrial revolution that occurred in the eighteenth century saw a major shift in many industries towards a more machine-centric production. Its inception can be traced back to England in 1760, with industrialisation paving its way to the United States as the eighteenth century came towards a close [15]. The following industrial revolutions brought further changes in various sectors improving technologies and overall quality of life. However, as technology evolved and the demands for production increased, downtime became a critical issue that needed to be addressed. To ensure that all machinery and systems are properly functioning, they require periodic maintenance. This necessitated the establishment of reliable and efficient maintenance practices, facilitating the seamless operation of industries while concurrently minimising downtime costs.

According to DIN 31051, maintenance is defined as “the combination of all technical and administrative measures as well as management measures during the life cycle of a unit of consideration to determine and assess the actual condition and to maintain the functional condition or return it to this condition so that it can fulfil the required function” [16]. Moreover, maintenance can be divided into four categories. These are reactive, preventive, predictive, and reliability-centred maintenance. Other than reactive maintenance, the other maintenance types focus on maintaining equipment before failure. This involves incorporating various technologies and techniques, such as non-destructive testing, to prevent downtime and ensure that the equipment or product complies with the relevant standards.

Non-destructive testing (NDT) is a branch of science that deals with the characterisation of materials without adversely affecting their functionality. It

offers a wide range of inspection techniques that operate on different sets of physical principles to assess materials based on their properties [17]. All NDT methods can be conducted throughout a component's life cycle. Inspections can be conducted in the manufacturing stage to ensure it complies with a set of standards or during the in-service stage to identify any damage that is present. Furthermore, it offers a cost-effective solution for conducting inspections on a single part or an entire production line [18].

While there are many NDT techniques, some of the most used are ultrasonic testing, visual inspection, radiography, microscopy, electromagnetic, and infrared thermography [19]. The requirement for NDT inspection stretches across various industries. These industries include the automotive [20], aerospace [21–23], oil and gas [24], and defence [25] industries. Figure 2-1 presents an overview of some of the NDT methods [26].

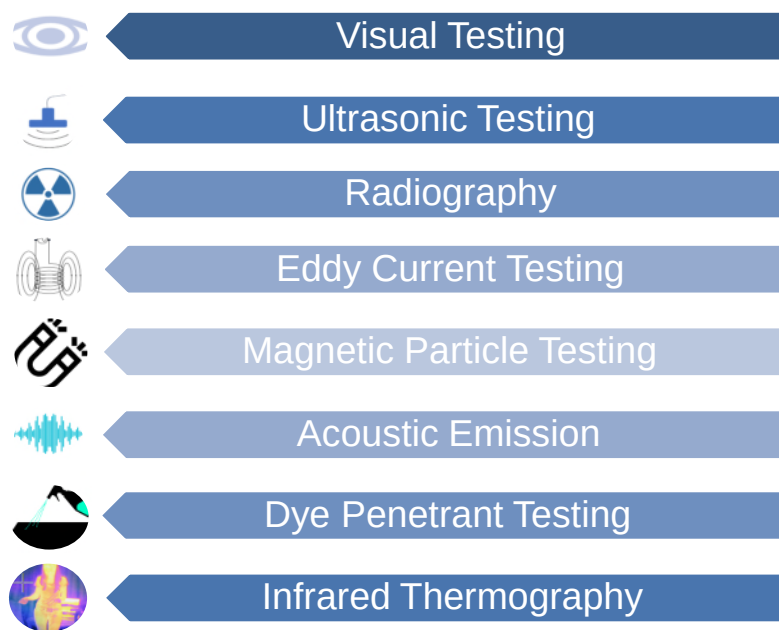


Figure 2-1 The various NDT methods

With the advent of Industry 4.0, concepts such as centralised decision making, digitalisation, artificial intelligence (AI), Big Data and the Internet of Things (IoT) have become pivotal in data creation and management. In the context of NDT, these emerging technologies can be incorporated to allow for more reliable and accurate inspections. Current literature suggests that the focus is tilted towards

the field of additive manufacturing (AM) [27,28], with X-ray computed tomography being the most reliable technique in assessing AM parts. However, the title of the most extensively used NDT technique lies with ultrasound testing (UT) [29]. Integrating ultrasonic inspection with the technologies available under Industry 4.0 can provide more valuable insights into the component's structural health. With increased computational power, more realistic numerical models have been developed for UT-based inspections [30]. Furthermore, the technique provides fast and computationally inexpensive methods to generate synthetic and augmented UT training data. However, the technique does not come without its drawbacks. The method requires a coupling agent between the component and the ultrasonic sensor. This is undesirable, especially in places where contacting the surface can adversely affect its properties. Moreover, the surface finish of the component must be smooth to achieve a reasonable signal-to-noise ratio, although methods such as water jet ultrasonic testing are able to circumvent this issue [31]. Lastly, the wave propagation speed of the material under testing must be known a priori.

Infrared thermography (IRT) is a non-contact, non-intrusive measurement technique operating in the infrared range of the electromagnetic spectrum, i.e., $\approx 0.7\text{--}100\text{ }\mu\text{m}$. It measures and records the thermal radiation emitted by an object's surface and characterises its thermal pattern with reference to its surrounding environment. All objects above 0 K emit electromagnetic radiation. This technique had its inception in the early 1970s when it was developed as an experimental technique resulting from the use of military infrared imagers [32]. The infrared radiometer captures the emitted energy, which can either be the inherent thermal energy of the specimen (passive mode) or induced into the specimen by a thermal excitation source (active mode). Within the active mode, thermal excitation can be achieved through several means: the fundamental principles governing the technique, the existing signal, and the image. Table 2-1 lists the most commonly reported active excitation methods in the literature and the types of defects they are capable of detecting. It is important to note that while the maximum detectable depth is listed for the optical methods, it is specifically for CFRPs and for an aspect ratio (defect size/depth) of 2.

Table 2-1 Active IRT methods

Method of Excitation	Source of Heat	Active IRT Terminology	Types of Defects Detected (Maximum Defect Depth Detected)	Advantages	Limitations	
Optical	Photographic flashes, lasers, or lamps	Optically Stimulated Thermography (OST)	Lock-in Thermography (LIT) [33–37]	Disbonding in coatings Delaminations Corrosion (3 mm) Defects in weld roots Cracks (surface/subsurface)	Allows for uniform heating. Less sensitive to local variations of surface emissivity	Long heating time Determining optimum modulation frequencies based on material properties Difficult to detect defects in planes perpendicular to the surface
			Pulsed Thermography (PT) [33,38–41]	Pitting Corrosion Delaminations Cracks (Surface/near surface) (6 mm) Defects in weld roots	Fast inspection time (few ms) Has numerous advanced post-processing algorithms	Heating is non-uniform Cannot detect defects deeper than 6 mm Difficult to detect defects in planes perpendicular to the surface
			Frequency Modulated Thermography (FMT) [42]	Pitting Corrosion Delaminations Cracks (Surface/subsurface) (4.5 mm)	Combines the advantages of PT and LIT for defect detection Uses multiple frequencies to detect defects at various depths	Cannot detect defects deeper than 6 mm below the surface Difficult to detect defects in planes perpendicular to the surface
			Pulsed Phase Thermography (PPT) [43]	Defects in weld roots Flat bottom holes		
			Step-Heating Thermography (SHT) [44]	Pitting Corrosion Delaminations Cracks (Surface/near surface) (3.5 mm) Defects in weld roots Flat bottom holes	Data captured during the heating and cooling phase Can detect damage deeper into the surface than PT	Longer inspection time compared to flash heating Difficult to detect defects in planes perpendicular to the surface
			Long Pulse Thermography (LPT) [45]	Pitting Corrosion Delaminations Cracks (Surface/near surface) (4.25 mm) Defects in weld roots Flat bottom holes	Useful for materials with low thermal conductivity	
			Laser-Line Thermography (LLT) [46–48]	Cracks (Surface/near surface) (5 mm)	Can detect defects in planes perpendicular to the surface	Longer inspection time compared to flash thermography Temperature sensitivity reduces for crack lengths below ~2 mm depth below ~1 mm and crack opening below ~5 μm
			Laser-Spot Thermography (LST) [48–50]	Cracks (Surface/near surface) (10 mm) Defects in weld roots		
			Ultrasonic	Ultrasonic horn/acoustic, air-coupled	Nonlinear Ultrasonic Stimulated Thermography (NUST) [51,52]	Cracks (surface/subsurface) (8 mm)

Electromagnetic	transducers, piezo-ceramic sensors				Uses a narrower frequency bandwidth for thermal excitation	
		Thermosonics, Sonic IR Thermography, and Vibro-thermography (Ultrasonic Stimulated Thermography) (UST) [53,54]		Cracks (surface/near surface) Delaminations (5 mm)	Suitable for in-depth damage Can detect closed cracks	Requires contact with the sample
	Microwaves	Microwave Thermography (MWT) [55,56]		Cracks (surface/subsurface) Voids Delaminations (38 mm) Material debonding	Fast inspection for large parts Volumetric heating Uniform heating	Microwave leakage is hazardous to human health High frequency required (890 MHz to 2.45 GHz) to minimize interference with communication services
	Eddy current induction	Pulsed Eddy Current thermography (PEC) [57–60]		Delaminations Cracks (surface/near surface) (4 mm)	Heating is not limited to specimen surface Lower SNR ratio compared to optical methods	Will not work with nonconductive materials Limited penetration depth compared to other techniques Cannot detect cracks that are very close to each other Dependent on crack geometry to estimate crack depth
Thermo-resistive radiation (for composites)	Embedded shape memory alloy wires with electric current		Shape Memory Alloy-based Thermography (SMaT) [61]	Cracks (surface/subsurface) (1.25 mm)	Does not require external heaters or complex signal-processing techniques Consumes less energy compared to other active IRT methods Can detect deep-lying defects Useful for in situ assessment	Inspection time is longer than optical excitation methods such as PT Does not cover wider range of materials than other excitation methods
	Embedded steel wires with electric current	Indirect Material-based Thermography (IMT)	Metal-based Thermography (MT) [62]	Delaminations Cracks (surface/subsurface) (8.25 mm) Material deformations	Removes the requirement for external heaters Removes the drawbacks of optical excitation caused by material anisotropy	
	Embedded carbon nanotubes with electric current		Carbon Nanotube-based Thermography (CNTT) [63]	Cracks (surface/near surface) Holes (1 mm)	Useful for in situ assessment Requires low power Does not require external heaters	
	Electrical current running through carbon fibre	Direct Material-based Thermography	Electrical Resistance Change Method (ERCM) coupled with thermography [64]	Cracks (surface/near surface) Indentation damage (6.5 mm)	Can detect defects at multiple angles	Detectability reduces at higher thermal conductivity values Applications are limited to materials with good electro-thermal properties

2.1.1 One-Dimensional Heat Diffusion

Figure 2-2 shows a schematic of a sample's response to electromagnetic radiation. Part of the radiation is reflected, and the other parts are absorbed by the sample, transmitted through, or radiated back from the sample's surface. For opaque materials, the transmitted radiation is zero. The absorbed radiation is in the form of heat, which can be observed using IRT, making it an ideal candidate for thermal material property evaluation.

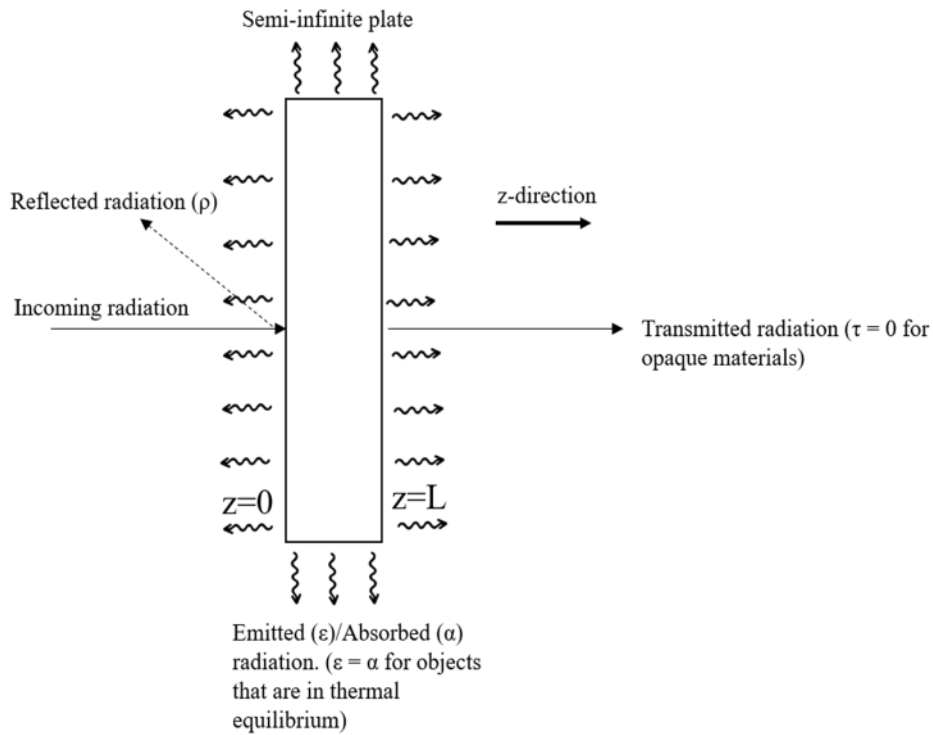


Figure 2-2 Schematic of 1D heat transfer on a semi-infinite plate with heat flowing in the z-direction (figure created in Microsoft PowerPoint)

The working principle using thermography for material characterisation is based on the classical heat diffusion theory in solids, which has the following equation, also known as the Fourier equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (2-1)$$

where $\alpha = \frac{k}{\rho C}$ is the *thermal diffusivity* of the material (m^2/s); k is the thermal conductivity (W/mK); ρ is the density (kg/m^3); and C is the specific heat ($\text{J}/\text{kg K}$).

Considering that the heat is uniformly distributed, the problem can be treated as a one-dimensional heat transfer problem, and Equation (2-1) is simplified to:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \quad (2-2)$$

where z is the direction in which heat travels (i.e., the thickness of the sample). Equation (2-2) has been addressed by Carslaw and Jaeger, assuming a semi-infinite and thermally insulated specimen whose initial temperature distribution is $T(z, 0)$ the temperature distribution can at any later time t be defined as [65]:

$$T(z, t) = \frac{1}{L} \int_0^L T(z, 0) dz + \frac{2}{L} \sum_{n=0}^{\infty} e^{\left(\frac{-n^2 \pi^2 \alpha t}{L^2}\right)} \times \cos\left(\frac{n \pi z}{L}\right) \int_0^L \frac{T(z, 0) \cos n \pi z}{L} dz \quad (2-3)$$

with L being the thickness of the sample.

2.1.2 Motivation for the Review

IRT has made significant advancements in the assessment of various materials. Numerous algorithms and methodologies have been developed, and their applications extend to various industries [38,66,67]. However, closer inspection of the current state-of-the-art method revealed that the majority of research has been focused on the reflection mode in active thermography. In this mode, the heat source and the infrared radiometer are placed on the same side of the specimen. Research concerning the transmission mode, i.e., the infrared radiometer and the heat source are on opposite sides of the specimen, is limited. Based on the author's understanding, there are several reasons that can explain this. One of the reasons is that, in many practical settings, the rear surface is not accessible, making inspections in the transmission mode impossible. Furthermore, the reluctance to explore through-transmission can also be attributed to the challenge in the depth quantification of subsurface defects, especially in pulsed thermography. Based on our current understanding, depth quantification is challenging since the distance travelled by the thermal wave in the sound and defect areas is the same [8]. Moreover, there is a lack of

theoretical/finite element models that simulate the back wall temperature behaviour exposed to heating on the front side. While these drawbacks have been holding through-transmission thermography behind its counterpart, the subsequent sections of this paper will reveal that there is a lot of potential for this technique and that it is an area of research worth developing. Furthermore, numerous studies have shown that transmission mode can enable the detection of deeper subsurface defects and, in many cases, improve lateral definition compared to reflection mode under certain material and experimental conditions, making it a more viable candidate for subsurface defect detection. The idea is to generate a greater interest in the transmission mode by identifying key research areas to develop the technique and transform it into an attractive solution for thermal material characterisation. With the emergence of modern technologies, the current drawbacks of through-transmission can potentially be overcome, allowing researchers to develop a better understanding of material and defect characteristics.

This state-of-the-art review seeks to uncover the existing capabilities of through-transmission thermography and identify the obstacles currently impeding its progress. The fundamental principles governing the technique, the existing signal, and image processing algorithms to evaluate raw thermographic data, as well as the materials assessed using this method, will be analysed. Finally, gaps that are hindering the progress of the technique will be identified and potential solutions will be recommended in order to overcome these gaps. To ensure transparency and repeatability, the methods used to conduct this review are outlined in the next section. It is important to emphasise here that this is a state-of-the-art review focused on the transmission mode. This may lead to many of the works of renowned experts in this field being omitted. This is simply due to the nature of the type of review and not due to bias on the researcher's side. The details of the review methodology are discussed in the next section.

2.2 Materials and Methods

To provide a comprehensive analysis of the current state-of-the-art in through-transmission thermography in a systematic way, the methodology outlined in the

book “Systematic approaches to a successful literature review” by Booth et al. [68] was adopted. Booth et al. define the literature review as “a systematic explicit, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work made by researchers, scholars, and practitioners”. The research framework is defined as the SALSA framework that seeks to Search, Appraise, Synthesise, and Analyse the available literature. These four steps will be explained in greater detail in the following subsections.

2.2.1 Search

Table 2-2 PICOC Framework

Concept	Definition	SLR Application
Population	The research area that will be targeted	Current methods using through-transmission thermography are not able to accurately characterise certain material characteristics
Intervention	Existing methodologies to address the defined problem	The various thermal excitation methods used to heat the specimen and the various signal reconstruction techniques to enhance the defect features such as defect shape, size, and depth
Comparison	Comparison between the proposed and existing techniques	The capabilities of the reflection mode in defect characterisation
Outcome(s)	Measurement criteria for testing effectiveness	The ability to successfully characterise the defects, measurement uncertainty, inspection time, etc.
Context	The specific target area of the population	Material characterisation of metals and composites

The first step in the SALSA framework is the search. To do so, it is essential to have a well-defined search scope. This, in turn, helps in crafting clear and concise research questions that can be successfully answered during the review. For this purpose, the PICOC framework, which stands for Population, Intervention, Comparison, and Outcome will be used. Table 2-2 explains the framework and indicates the relevance of each concept to this systematic literature review (SLR).

2.2.2 Research Aim and Objectives

Defining the research scope using the PICOC framework, the following aim, objectives, and three research questions have been derived. The aim of this review is to investigate the current capabilities of through-transmission thermography and identify the research gap that currently exists using this method. The research aim will be achieved by accomplishing the following set of objectives.

1. Identify the capabilities of through-transmission thermography for thermal material property evaluation.
2. Explore the current state-of-the-art in through-transmission thermography.
3. Identify the limitations of through-transmission thermography in terms of material characterisation.

Based on the research aim and objectives, three research questions that this paper will answer are the following:

1. How effectively can through-transmission thermography evaluate thermal material properties?
2. What are the fundamentals (definition, working principle, application) and the current state-of-the-art in through-transmission thermography for material and defect characterisation?
3. What advantages and/or limitations does the transmission mode have in terms of defect and material characterisation compared to the reflection mode?

After defining the research scope, the resulting aim, objectives, and the research questions, to ensure that the conducted literature review can be defined as systematic, an appropriate search strategy needs to be implemented. The resulting papers then have to be screened based on certain inclusion and exclusion criteria outlined in Table 2-3 to ensure that the final set of papers is within the scope of this review. To accomplish this, the database Scopus was used, as it covers both journal articles and conference papers that can be selected to be part of this review.

To ensure the review covers all available literature on active thermography using transmission mode, synonymous terms were also included in the search strings. For example, for the transmission mode of infrared thermography, the phrase “through–transmission” is synonymous with “transmission mode”. However, searching the terms “through–transmission” and “thermography” yields results related to ultrasound testing where the “through–transmission” method is widely used as well (e.g., through-transmission laser welding). To exclude these results, a specific exclusion criterion was added to limit the search results to thermography. It is also important to note that, to include papers discussing material characterisation, the search was limited to thermal material properties, which is why the term “thermal diffusivity” was used as part of the search strings. A detailed overview of the search strings is shown in Table 2-4. To manage the selected references, Mendeley (<http://www.mendeley.com> accessed on 10th July 2024) was used for its ease of access, add-in for Microsoft Word for in-text citation (which has been used for writing this paper), and an integrated pdf viewer, which allows its users to download available articles so that they can be uploaded and viewed on Mendeley directly.

Table 2-3 Inclusion and exclusion criteria

Inclusion criteria (IC)	Publications related to active thermography
	Publications dealing with material characterisation
	Publications related to through-transmission thermography
Exclusion criteria (EC)	Does not meet inclusion criteria
	Full paper not available
	Papers using thermography in the medical industry
	Publications not in English
	Publications before the year 2008

Table 2-4 Search strategy

Database	Scopus
Search strings	TITLE-ABS-KEY (thermal AND diffusivity AND measurement AND thermography)
	TITLE-ABS-KEY (“thermography” “transmission mode”)
	TITLE-ABS-KEY (“thermography” AND “through transmission” AND NOT “electron microscope” AND NOT “transmission line”

AND NOT “ultrasonic” AND NOT “electron microscopy” AND NOT “electron microscopies” AND NOT “transmission welding” AND NOT “electron” AND NOT “transmission weld” AND NOT “laser weld” AND NOT “laser welding”)	
Type of article	Journal or conference

2.2.3 Appraisal

The second step in the SALSA framework is the appraisal, where the papers resulting from the search string need to be evaluated and either included or excluded based on the criteria shown in Table 2-3. The literature search using the strings mentioned in Table 2-4, which ran on the 1st of July 2024, yielded a total of 379 results. Then, based on the specific inclusion and exclusion criteria, the total number of papers was narrowed down to 81. These articles are then used for the next parts of the review.

2.2.4 Synthesis

The next phase in the systematic literature review is the synthesis phase. This phase involves the extraction and classification of information from the final selection of articles to help answer the research questions mentioned in Section 2.2.2 during the search phase. To be able to do this in an efficient and systematic way, the articles were tabulated in Microsoft Excel. The included papers were then analysed and evaluated based on their reporting quality in several key areas considered important for addressing the research questions.

Furthermore, since this paper employs a mixed synthesis strategy, the publication elements of the papers are also selected as part of the synthesis process. Table 2-5 shows all the records selected for this phase of the review.

Table 2-5 Elements for synthesis analysis

Quantitative Elements	Authors
	Keywords
	Type of Paper (Journal/Conference)
	Year of Publication
Qualitative Elements	Definition and Materials
	Working principle of the technique
	Data processing algorithms

2.2.5 Analysis

The analysis phase of the systematic literature review involves extracting the relevant information from the final selection of papers. This phase can be divided into two parts. The first part is a thematic analysis, which includes the quantitative and qualitative elements listed in Table 2-5 and correlates these elements with the selected list of papers. The next step will evaluate the selected studies to answer the research questions outlined in Section 2.1. Finally, the last step is the conclusion, which provides a brief summary of what this review had set out to achieve and to what extent it has managed to do so. It will also highlight some of the key findings in the review and provide some insight into future research opportunities.

The following subsections will describe the qualitative and quantitative elements used in this review in greater detail.

2.2.6 Quantitative Elements

The quantitative elements mentioned in Table 2-5 are the basic elements extracted from the selected articles before full-text reading:

1. Authors;
2. Keywords;
3. The type of paper, whether it is a journal or conference paper and which journal or conference the paper has been published in;
4. Year of Publication.

2.2.7 Qualitative Elements

This review also addresses the qualitative elements of the review. These elements will aid in identifying the current research gap in through-transmission thermography and help answer the research questions that were mentioned in an earlier section of the paper. These elements include the following:

1. Definition of the said technique and the materials used to apply the mentioned technique;
2. Working principle of the techniques used;
3. Data processing algorithms;
4. Data analysis;
5. Conclusion and future work.

2.2.7.1 Definition and Materials Used

The first element analysed for the thematic synthesis is the definition and materials. The final set of selected papers was screened to observe how they define the technique used, whether it is the reflection or the transmission mode. With regards to materials, the industries that use thermography for applications such as structural integrity often tend to use metal alloys, such as titanium and nickel alloys [20–22], as well as composite materials such as CFRPs [69–71]. This has led to a lot of research effort being focused towards developing novel techniques to evaluate their material properties. Furthermore, this review also includes all the equipment used to conduct the experiment and/or simulations as part of the materials.

2.2.7.2 Working Principle

As mentioned at the beginning of this paper, each NDT method operates on a set of physical principles that govern it. Therefore, the working principle element of the qualitative analysis will evaluate how the authors explain the physics/operating principles of through-transmission thermography. Similarly, as mentioned in the previous subsection, the evaluation of the working principle will not be limited to just through-transmission thermography but will also include the working principles of the thermal excitation method.

2.2.7.3 Data Processing Algorithms

Raw thermograms often have noise from various sources embedded in them, which can make distinguishing actual data challenging. To eliminate this noise, numerous signal and image reconstruction algorithms have been developed. This

part of the qualitative analysis will explore the various algorithms and how they are used to improve the raw data.

2.2.7.4 Data Analysis

The data analysis element of the review explores the methods used to analyse and interpret the data obtained and the implications it has. This can include data visualisation in the form of graphs to describe trends and/or anomalies in the data and an explanation of the behaviour. Furthermore, quantities such as repeatability and measurement uncertainty will also be evaluated to determine the quality of the data presented.

2.2.7.5 Conclusions and Future Work

The final qualitative element used as part of the analysis is the conclusion and future work. The continuous and evolutionary state of research dictates that no study will be comprehensive and will have certain limitations that need to be explored further. This review will evaluate the conclusions the authors have drawn from their research and what limitations they have identified. This part of the review is crucial as it highlights the current state-of-the-art and the limitations of through-transmission thermography.

2.3 Results

This section of the paper presents the findings of the final selection of papers used for this review. It is divided into two subsections; the first is a quantitative analysis that includes the quantitative elements defined in Table 2-5 in the previous section, followed by a qualitative analysis using the elements defined in the same table.

2.3.1 Quantitative Analysis

Figure 2-3 shows the number of authors that have at least two or more publications in the final selection of papers. From the figure, it can be seen that Salazar, Mendioroz, and Maldague have the greatest number of publications, with four each. This is followed by Sfarra, Mayr, Krishnamurthy, Kalyanavali,

Ishizaki, Ibarra, Balasubramaniam, and Avdelidis, each of them having three publications. The rest of the authors have two.

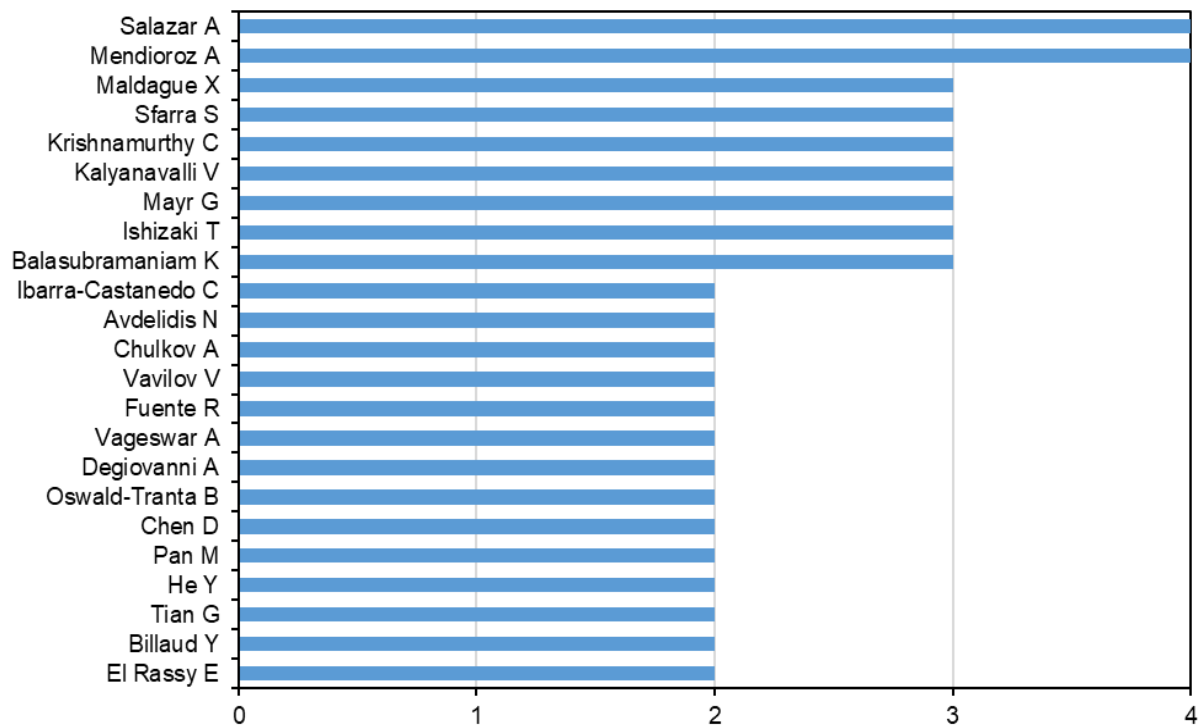


Figure 2-3 Names of authors with two or more publications

Figure 2-4 shows the most common keywords for the final selection of papers appearing at least three times or more. The phrase “thermal diffusivity” is the most commonly used term, which makes sense as it was also one of the search terms. This was followed by “infrared thermography”, which appeared 15 times. Other common keywords, while occurring more than three times, appeared in less than ten instances.

Table 2-6 and Table 2-7 show the names of the journals and conferences, respectively, along with the papers that were published in them. The journal that had the greatest number of publications was NDT and E International, with 6 publications, and the conference in which most of the papers were presented was Thermosense, which had 11 out of the 22 publications. Overall, studies have been published in different journals with varying scopes, highlighting the versatility of the technique.

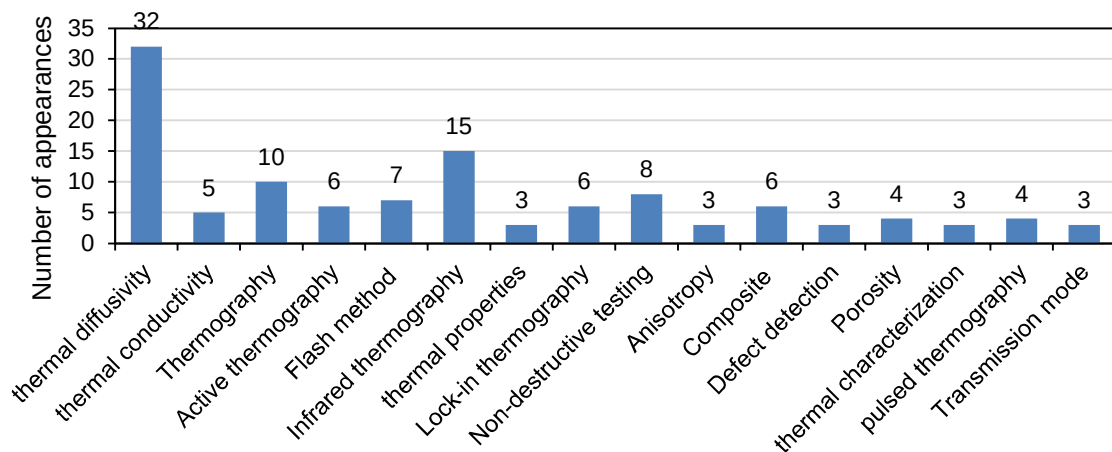


Figure 2-4 Common keywords (occurring at least 2 or more times)

Table 2-6 List of journals and their related publications

Journal Name	Ref.
Acta Material	[72]
Advances in Optical Technologies	[73]
Ceramics	[74]
Composite Structures	[75]
Composites Part B: Engineering	[4]
Composites Science and Technology	[76,77]
IEEE Transactions on Industrial Informatics	[78]
Infrared Physics and Technology	[79]
Int J Thermophys	[80–84]
International Journal of Thermal Sciences	[85,86]
International Journal of Thermophysics	[87–91]
J. Phys. Chem. C	[92]
Journal of Applied Physics	[93]
Journal of Heat Transfer	[94,95]
Journal of Materials Engineering and Performance	[96]
Journal of Non-destructive Evaluation	[97–100]
Journal of Power Sources	[101]
Journal of the American Chemical Society	[102]
Materials	[6,10]
Materials Letters	[103]
Measurement	[104,105]
Measurement Science and Technology	[106–108]
Measurement: Journal of the International Measurement Confederation	[109]

Mechanical Systems and Signal Processing	[110]
Mechanics and Industry	[111]
Metals	[112]
Metrologia	[113]
MRS Advances	[114]
NDT and E International	[57,71,115–118]
Non-destructive Testing and Evaluation	[119]
Polymer Composites	[120]
Quantitative InfraRed Thermography Journal	[121–125]
Science and Technology of Advanced Materials	[126]

Table 2-7 List of conferences and their related publications

Conference Name	Ref.
17th International Workshop on Advanced Infrared Technology and Applications	[127]
2014 IEEE 20th International Symposium for Design and Technology in Electronic Packaging, SIITME 2014	[128]
2016 6th Electronic System-Integration Technology Conference, ESTC 2016	[129]
2019 8th International Conference on Modeling Simulation and Applied Optimization, ICMSAO 2019	[130]
Procedia CIRP	[131]
Procedia Structural Integrity	[132]
Proceedings—Electronic Components and Technology Conference	[133]
Sixteenth International Conference on Quality Control by Artificial Vision	[134]
Smart Materials and Non-destructive Evaluation for Energy Systems IV	[135,136]
SPIE/COS Photonics Asia	[137]
Thermosense: Thermal Infrared Applications XLV	[138–142]
Thermosense: Thermal Infrared Applications XL	[143]
Thermosense: Thermal Infrared Applications XLIII	[144]
Thermosense: Thermal Infrared Applications XXXIV	[145]
Thermosense: Thermal Infrared Applications XXXIX	[146]
Thermosense: Thermal Infrared Applications XXXVII	[147,148]

The pie chart in Figure 2-5 shows the distribution of publications among journals and conferences. Out of the 82 papers selected, 73% (60) were published in journals, and the remaining 27% (22) of papers were published in conferences.

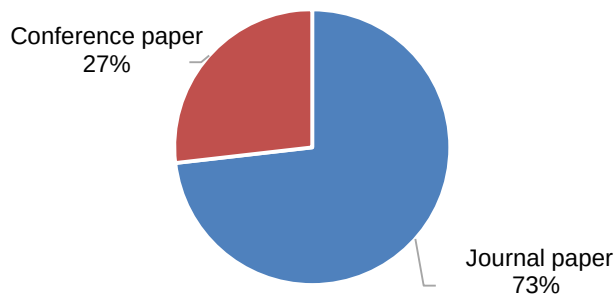


Figure 2-5 Distribution of papers published in journals and conferences

The number of publications per year from the selected list of papers is displayed in Figure 2-6. Most of the publications seem to be between 2014 and 2018. There is no trend in terms of increasing or decreasing publications except for a decrease seen between 2009 and 2011. On average, there are five publications per year. It is also important to mention here that while there have been publications in 2024, these papers have been excluded since they do not meet the inclusion criteria of this review. The limited number of papers throughout the years can be attributed to the lack of popularity of the transmission mode compared to the reflection mode.

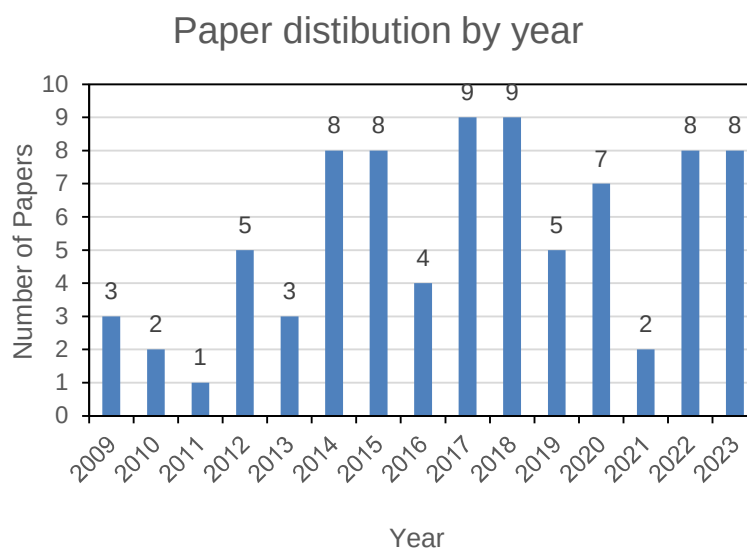


Figure 2-6 Number of publications per year

2.3.2 Qualitative analysis

The following subsections evaluate the selected list of papers based on the qualitative elements listed in Table 2-5.

2.3.2.1 Definition and Materials

The definition and materials element in this review is associated with the definition of through–transmission. The materials are simply the specimen, and the equipment used for capturing data. With respect to the definition of through-transmission thermography, most of the selected papers define the technique as heating the specimen on one side and placing the camera on the opposite side of the specimen [4,6,115,124,143,144]. Other studies do not explicitly provide a definition for the transmission mode but do provide a schematic of the through-transmission configuration [57,73,99,135]. For the materials, the standard experimental setup consists of a specimen that needs to be inspected, a heat source, and an infrared radiometer. However, conducting purely numerical/simulation-based research nullifies this requirement, as computer software is used instead. The literature search revealed that the most common heating source for active thermography in transmission mode includes flash lamps, laser pulse, eddy current coils, and halogen lamps.

Based on the final selection of papers, most of the papers focused on evaluating the material properties of composite materials, which is evident in [73,75,78,99,135]. Composite materials such as CFRPs have become increasingly popular in various industries, such as the shipbuilding, aerospace, automotive, and sports industries [149]. Their success could be attributed to their high strength-to-weight ratios. Another popular material is steel. As mentioned in an earlier section, in this context the term *materials* includes not only the physical substances but also the software packages used for numerical and computational analyses. For this purpose, the literature shows that the finite element software COMSOL is a popular choice for performing numerical analysis [94,118,119,146]. Another popular commercially available software used for finite element analysis (FEA) analysis is ANSYS [124,144]. Based on the author's experience using both software, COMSOL may be the preferred software, as it is more user friendly,

allows for Multiphysics modelling, and allows the user to input their own equations. However, ANSYS offers better meshing and more robust solvers; hence, it is used more than COMSOL in the industry.

2.3.2.2 Working Principle

The next element for qualitative evaluation is the working principle. While the definition element defines what the technique is, the working principle explains the physics behind the technique. For through-transmission pulsed thermography, most of the selected papers adopt Parker's model (Equations (2-4) to (2-6)) [12]. Motivated by the solution presented by Carslaw and Jaeger (Equation (2-3)), Parker et al. provided a solution to the 1D heat transfer problem by addressing two major obstacles that lead to difficulties in solving the classical heat conduction equation. Firstly, a flash excitation is introduced to eliminate the thermal contact resistance between the heat source and the sample. Secondly, the effect of surface heat loss is removed by taking the heat measurements in a very short period of time so that the cooling time is reduced to a minimum. Using these two conditions, any semi-infinite homogenous material with thickness L subjected to a Dirac pulse of energy Q , the temperature evolution with respect to time can be described by the following relationship [12]:

$$T(L, t) = \frac{Q}{\rho CL} \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp \left(-n^2 \pi^2 \frac{\alpha t}{L^2} \right) \right] \quad (2-4)$$

In the equation, a dimensionless quantity F can be introduced, where $F = \frac{\alpha t}{L^2}$ is the Fourier number that characterises a material's transient heat conduction. It is the ratio of the material's diffusive rate to its storage rate. To make the equation above independent of material properties and dimensions, Parker introduces two dimensionless quantities $V = \frac{T}{T_M}$, which is a ratio of the temperature to the maximum temperature T_M the backwall can reach and $\omega = \frac{\pi^2 \alpha t}{L^2}$, which is the dimensionless quantity of time. Using this relation, Equation (2-4) is then reduced to:

$$V(L, t) = \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp(-n^2 \omega) \right] \quad (2-5)$$

Figure 2-7 shows the reflection and transmission configurations of flash thermography along with their corresponding time vs. temperature plots generated on MATLAB R2023a using Equation (2-5). To generate Figure 2-7a, the $(-1)^n$ term is removed to show the temporal behaviour at the front wall. Additionally, to show the temporal behaviour when a defect is introduced, Figure 2-8 was generated on COMSOL v.6.0, a commercially available finite element modelling software. The sample was a 200mm × 150mm × 10 mm steel plate with thermal conductivity $k = 45$ W/mK, density $\rho = 7850$ kg/m³, and specific heat capacity $C = 475$ kJ/kgK. The defect was an airgap in the shape of a circle with a radius of 8 mm, and the depth of the defect was 1 mm from the front wall. The above method for through-transmission is currently the standard and is used for determining the thermal properties of materials also used by commercial apparatus such as the laser flash apparatus Netzsch LFA 427 [150]. This system evaluates the thermal diffusivity of a material using Parker's half-rise equation. The method utilises the time taken for the temperature to reach half the maximum temperature, where $\omega = 1.38$. If the length of the sample is known, the thermal diffusivity (m²/s) can be evaluated using the following formula:

$$\alpha = \frac{1.38L^2}{\pi^2 t_{\frac{1}{2}}} \quad (2-6)$$

While Parker's method has remained the most popular choice for determining thermal properties, there have been some efforts to develop novel techniques in through-transmission thermography. One such effort can be seen in a paper published by Chihab et al. [87]. The paper provides a more novel and efficient formula for calculating thermal diffusivity by addressing an issue that Parker fails to consider, which is heat losses in the rear and front faces. According to the method, the thermal diffusivity can be expressed as a function of the natural logarithm of the backwall temperature curve's descending part as well as the Biot number relative to the front and backwall heat losses. This is achieved by solving

the transient heat conduction equation using Green's function. Then, in the Laplace domain, the integral expressions for the front and backwall temperatures are calculated using the analytical solution ranging from 0 to $+\infty$. Approximating the solution numerically yields a formula for the Biot number on the rear face.

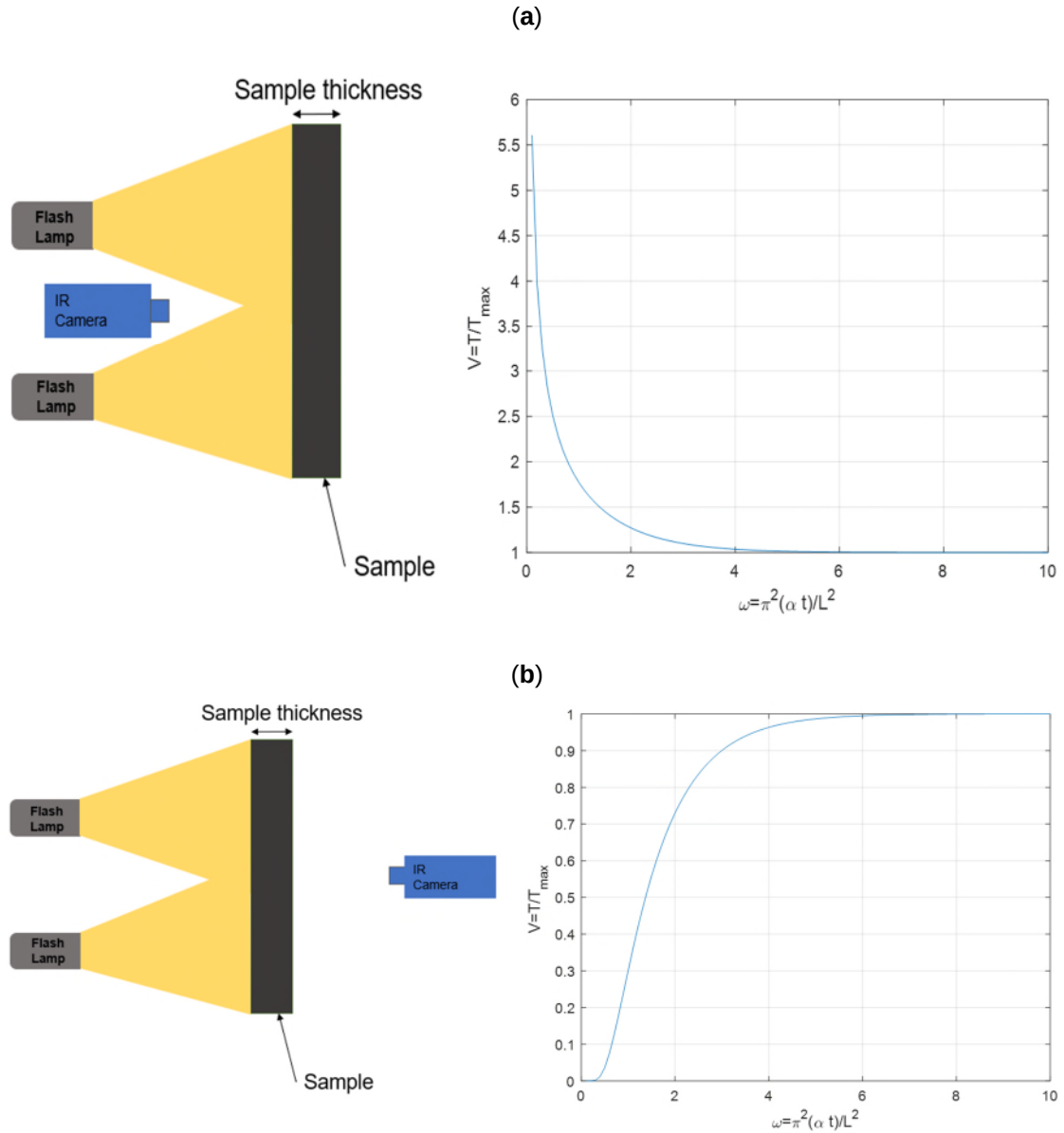


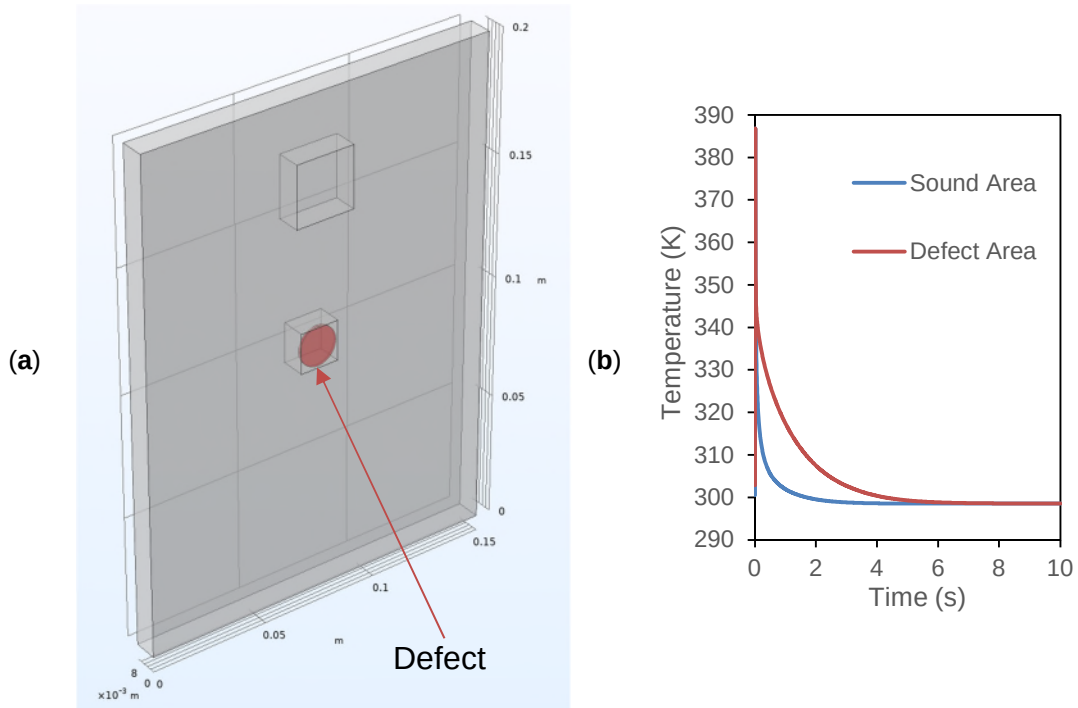
Figure 2-7 (a) The reflection and (b) transmission configurations with their respective temperature profiles (graphs have been generated using MATLAB R2023a).

To identify defects in structures, the temperature curve can be observed from either the front or back surface. A deviation of the curve in the defected zone compared to the sound area can be used to determine the defect properties. Vageswar et al. [119] utilises the deviation of temperature to measure wall thinning, which is a common material degradation mechanism for corrosion. In the paper, the slope of the temperature contrast between the defect and the defect-free zones is determined. Then, the first derivative of the curve is used to determine the defect depth. The slope reaches a maximum, referred to as the peak slope time, t_d .

The paper also concludes that the peak slope time is proportional to the square of the defect. Furthermore, as long as the ratio between the defect length and the defect-free length, L_d/L is less than 0.5, the peak slope time can be calculated using the defect length as shown below [119].

$$t_d = \frac{0.9L_d^2}{\pi^2\alpha} \quad (2-7)$$

Alternatively, if the ratio exceeds 0.5, then in the above equation, 0.9 needs to be replaced by another factor from the graph, which displays the variation in the proportionality factor ω_d with L_d/L .



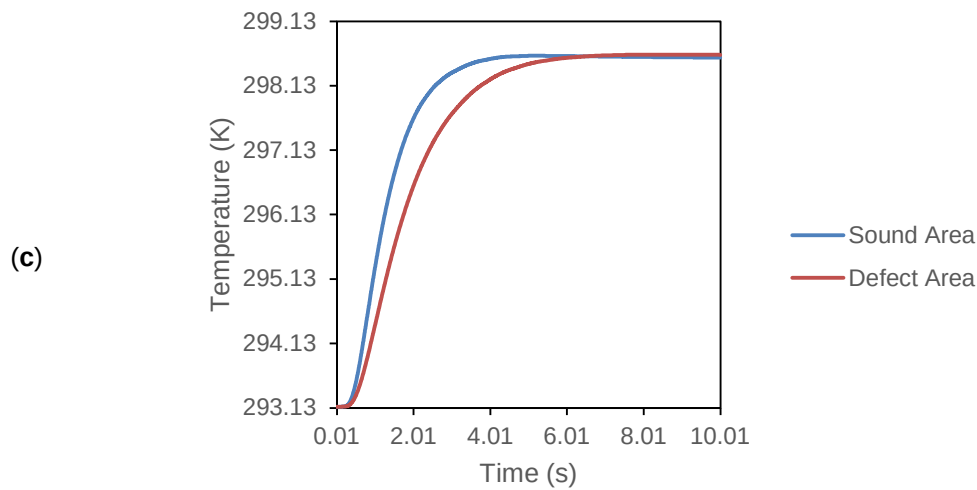


Figure 2-8 (a) Schematic for pulsed thermography using COMSOL v.6.0 with the temperature response of the defect and defect-free areas for an 8 mm radius defect at 1 mm depth (as viewed from the front wall) at the (b) front wall (c) back wall. Plots have been generated using Microsoft Excel v.2406

An important material property that has been the focus of many of the selected papers is the determination of the material thermal diffusivity. The thermal diffusivity is a parameter that governs how quickly the temperature of a material will change when heated. As mentioned in an earlier section, it is dependent on the material's thermal conductivity k (W/mK), its density ρ (kg/m³), and its specific heat C (J/kg K). Defect characterisation is possible by observing the change in material thermal diffusivity between the defect and the defect-free zones. The change in the defect zone will cause a temperature change different from the one observed in the defect-free zone. Furthermore, thermal diffusivity measurements have also been linked to the integrity assessment of thermal barrier coatings TBCs [73]. It has been observed that there is an increase in thermal diffusivity from smaller fractions of spent life and decreases at higher fractions. A non-monotonic trend is observed between the thermal diffusivity and the spent life. The cause for this has been attributed to the progressive growth of cracks and their propagation parallel to the boundary between the TBC top layer and bond coat during the cyclic oxidation tests, which caused an increase in thermal diffusivity. This effect is nullified at longer times, where a decrease in thermal

diffusivity is observed. The effect on thermal diffusivity due to progressive cracks inside the TBC can be used to estimate the degree of damage.

Most papers address the challenge of thermal diffusivity through the thickness of the material. This diffusivity is labelled as the transverse diffusivity, as reported in [77]. The transverse diffusivity is defined as the diffusivity measured in the direction perpendicular to the x-y plane of a sample. For this purpose, the 1D heat flow approximation of Equation (1) is valid and adequate for determining the material thermal diffusivity. Another assumption made in this process is that the inspected material is isotropic, which means its intrinsic properties are independent of orientation. For anisotropic materials, this is not the case, so the 1D heat approximation derived for the z-direction (through thickness) no longer holds. Here, the longitudinal thermal diffusivity, i.e., the diffusivity measured parallel to the x-y plane also needs to be measured in order to obtain a thorough assessment of the material's thermal properties. Equations (2-8)–(2-14) [77] describe this process. First, the temperature response $T(x,y,t)$ is measured using an infrared camera. This results in time series data, which are then converted in terms of spatial frequencies using the Fourier transform, and thus, the following equation is obtained:

$$\theta(\alpha_n, \beta_m, z, t) = \int_0^L \int_0^l T(x, y, z, t) \cos(\alpha_n x) \cos(\beta_m y) dx dy \quad (2-8)$$

where L and l are the dimensions of the sample in the x and y directions, $\alpha_n = \frac{n\pi}{L}$ and $\beta_m = \frac{m\pi}{l}$ are the discrete eigenvalues for the boundary conditions in the x and y directions. Performing a Laplace transform on Equation (2-8) yields:

$$\theta(\alpha_n, \beta_m, e, p) = \frac{F(\alpha_n \beta_m)}{\sinh(\gamma e) \left(\lambda_m \gamma + \frac{h^2}{\lambda_z \gamma} \right) + 2h \cosh(\gamma e)} \quad (2-9)$$

where γ is:

$$\gamma = \sqrt{\frac{p + a_x \alpha_n^2 + a_y \beta_m^2}{a_z}} \quad (2-10)$$

where $F(\alpha_n \beta_m)$ is the Fourier transform coefficient of $f(x, y)$ and a_x, a_y, a_z are the thermal diffusivities in the x, y, and z directions. It is important to mention here that:

$$\theta(\alpha_n, \beta_m, e, p) = S(\alpha_n, \beta_m, p + k) \quad (2-11)$$

with:

$$k = a_x \alpha_n^2 + a_y \beta_m^2 \quad (2-12)$$

Therefore, leveraging the shift property in Laplace space, a straightforward expression can be derived in the simple Fourier space:

$$\frac{\theta(\alpha_n, \beta_m, e, t)}{\theta(0,0, e, t)} = \frac{F(\alpha_n, \beta_m)}{F(0,0)} \cdot \exp(-kt) \quad (2-13)$$

where $\theta(0,0, e, t)$ is the temperature average of the rear face multiplied by its surface:

$$\bar{T}(t) = \left(\int_0^L \int_0^l T(x, y, e, t) dx dy \right) / lL = \frac{\theta(0,0, e, t)}{lL} \quad (2-14)$$

Equation (2-13) can be used to estimate a_x by setting $\alpha_n \neq 0$ and $\beta_m = 0$ or a_y by setting $\beta_m \neq 0$ and $\alpha_n = 0$.

Another important factor that most papers consider is that the material under assessment is usually opaque. Based on the final selection of papers, three explicitly discuss the assessment of semi-transparent materials. Pawlak et al. [108] discuss the use of lock-in thermography to assess a GaAs semi-transparent wafer. The theoretical model is described by Equations (2-15)–(2-17) [108]. Firstly, the photothermal infrared radiometry (PTR) signal in the transmission configuration is written as:

$$S_1(f, \beta_{ext}, \beta_{IR}) \propto \int_0^L \beta_{IR} \cdot \Delta T_1(z, \beta_{ext}) \cdot \exp(-\beta_{IR} \cdot (L - z)) dz \quad (2-15)$$

where β_{ext} is the optical absorption coefficient of the material at the wavelength of the excitation source and $\Delta T_1(z, \beta_{ext})$ is the thermal wave field equation, L is

the sample thickness, f is the modulation frequency, and β_{IR} is the infrared absorption coefficient. Assuming 1D approximation, the PTR signal can be written as:

$$S_{trans}(\omega, \beta_{eff,IR}) = \frac{T_1 \beta_{eff,IR}}{2k_m(\beta_{eff,IR}^2 - \sigma_t^2)} \times \left[\frac{2(g+t) - [(t+1)(1+g)e^{\sigma_1 L} + (t-1)(1-g)e^{-\sigma_1 L}]e^{-\beta_{eff,IR} L}}{(1+g)^2 e^{\sigma_1 L} - (1-g)^2 e^{-\sigma_1 L}} \right] \quad (2-16)$$

Here, T_1 is the instrumental factor $t(\omega) = \frac{\beta_{eff,IR}}{\sigma_t(\omega)}$, $\sigma_t(\omega) = \sqrt{\frac{i\omega}{\alpha_{id}}}$ where α_{id} is the thermal diffusivity, $g = k_g \cdot \frac{\sqrt{\alpha_{id}}}{k_{id}} \cdot \sqrt{\alpha_0}$, k_{id} is the thermal conductivity of the material, $\omega = 2\pi f$. The effective infrared absorption coefficient β_{eff} is the weighted average value of the infrared absorption coefficient and given by the relation:

$$\beta_{eff,IR} = \frac{\int_{\lambda_{min}}^{\lambda_{max}} R_{det}(\lambda) W'_{\lambda} \beta_{IR}(\lambda) d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} R_{det}(\lambda) W'_{\lambda} d\lambda} \quad (2-17)$$

β_{IR} is defined as the IR absorption spectrum of the sample. The sensitivity limits of the detector are denoted by λ_{max} and λ_{min} , the spectral sensitivity of the detector is $R_{det}(\lambda)$, and finally, the temperature derivative of Planck's expression for the spectral radiance is given by $W'_{\lambda} = \left(\frac{\partial W}{\partial T} \right)_{\lambda}$.

For pulsed thermography, Salazar et al. [107] derived Equations (2-18)–(2-25) to effectively extend the original flash method introduced by Parker and applied it to measure the thermal diffusivity of semi-transparent solids. Here, a semi-transparent slab with thickness L is used as an example that is thermally excited using a light beam with wavelength λ and intensity I_0 . Using the Beer–Lambert law and taking multiple reflections of the incident light beam, the light intensity inside the sample can be written as:

$$I(z) = I_0(1-R)e^{-\alpha z} + I_0(1-R)e^{-\alpha z} R e^{-\alpha(L-z)} + I_0(1-R)e^{-2\alpha L} R^2 e^{-\alpha z} + \dots \quad (2-18)$$

$$= \frac{I_o(1-R)(e^{-\alpha z} + Re^{-2\alpha L}e^{\alpha z})}{1 - R^2e^{-2\alpha L}}$$

where R and α are the optical reflection and absorption coefficients of the slab at the wavelength of the incident light beam (λ), respectively. The Laplace transform for the heat diffusion equation is then written as:

$$\frac{d^2\bar{T}}{dz^2} - q^2\bar{T} = \frac{\bar{P}_o(1-R)\alpha(e^{-\alpha z} - Re^{-2\alpha L}e^{\alpha z})}{K(1 - R^2e^{-2\alpha L})} \quad (2-19)$$

where the Laplace transform of the sample temperature is expressed by the symbol $\bar{T}$, and the temporal shape of the light beam is denoted by $\bar{P}_o$. The thermal conductivity of the sample is K and $q = \sqrt{\frac{s}{D}}$, s is the Laplace variable, and D is the thermal diffusivity of the material. Neglecting the thermal conduction due to the surrounding gas, the general solution to Equation (19) can be written as a superposition of the solution to the homogeneous equation with a particular solution of the non-homogeneous equation:

$$\bar{T}(z) = Ae^{qz} + Be^{-qz} + Ce^{-\alpha z} + Ee^{\alpha z} \quad (2-20)$$

The coefficients of the particular solution are given by:

$$C = \frac{\bar{P}_o(1-R)\alpha}{2K(q^2 - \alpha^2)} \quad (2-20a)$$

$$E = \frac{\bar{P}_o(1-R)\alpha Re^{-2\alpha L}}{2K(q^2 - \alpha^2)} \quad (2-20b)$$

To obtain constants A and B in Equation (2-20), the boundary conditions applied to the sample surfaces are used:

$$K \left. \frac{d\bar{T}}{dz} \right|_{z=0} = h\bar{T}(z=0) \quad (2-21)$$

$$K \left. \frac{d\bar{T}}{dz} \right|_{z=L} = h\bar{T}(z=L) \quad (2-21b)$$

where the linear coefficient of heat transfer is h , which takes into consideration the combined effect of convective and radiative heat transfer. Assuming h is the same at both surfaces, the Laplace transform of the temperature inside the sample is given by:

$$\bar{T}(z) = C \left(\frac{A_0 e^{qz} + B_0 e^{qz}}{E_0} + e^{-\alpha z} \right) + E \left(\frac{A_1 e^{qz} + B_1 e^{qz}}{E_0} + e^{-\alpha z} \right) \quad (2-22)$$

where:

$$A_0 = e^{-qL} \left(q - \frac{h}{K} \right) \left(\alpha + \frac{h}{K} \right) + e^{-\alpha L} \left(q + \frac{h}{K} \right) \left(-\alpha + \frac{h}{K} \right) \quad (2-23)$$

$$B_0 = e^{qL} \left(q + \frac{h}{K} \right) \left(\alpha + \frac{h}{K} \right) + e^{-\alpha L} \left(q - \frac{h}{K} \right) \left(-\alpha + \frac{h}{K} \right) \quad (2-23b)$$

$$A_1 = e^{-qL} \left(q - \frac{h}{K} \right) \left(-\alpha + \frac{h}{K} \right) + e^{\alpha L} \left(q + \frac{h}{K} \right) \left(\alpha + \frac{h}{K} \right) \quad (2-23c)$$

$$B_1 = e^{qL} \left(q + \frac{h}{K} \right) \left(-\alpha + \frac{h}{K} \right) + e^{\alpha L} \left(q - \frac{h}{K} \right) \left(\alpha + \frac{h}{K} \right) \quad (2-23d)$$

$$E_0 = e^{-qL} \left(q - \frac{h}{K} \right)^2 + e^{-qL} \left(q + \frac{h}{K} \right)^2 \quad (2-23e)$$

As mentioned in previous equations for semi-transparent materials, a variable β is introduced. This variable represents the effective IR absorption coefficient for the sample under observation. The reason for introducing this variable is because, for semi-transparent materials, the signal recorded by the infrared radiometer does not only come from the sample surface but also from the bulk. Keeping this in mind, the Laplace transform of the signal recorded by the infrared radiometer in the transmission configuration is:

$$\bar{S}(L) = F \int_0^L \beta e^{\beta(z-L)} \bar{T}(z) dz \quad (2-24)$$

The constant F includes the emissivity of the sample, detectivity, and the sensor area, as well as the temperature derivative of the Planck function at room temperature. It also includes the effect of multiple reflections of the IR emission in the walls of the sample. $\bar{T}(z)$ is the Laplace transform of the sample

temperature given in Equation (2-22). Substituting Equation (2-22) into Equation (2-24) and analytically solving the integral Laplace transform of the recorded IR signal is given by:

$$\begin{aligned}\bar{S}(L) = FC \frac{\beta e^{-\beta L}}{E_o} & \left[-\frac{A_0}{q + \beta} (1 - e^{(\beta+q)L}) + \frac{B_o}{q - \beta} (1 - e^{(\beta-q)L}) \right. \\ & \left. + \frac{E_o}{\alpha - \beta} (1 - e^{(\beta-\alpha)L}) \right] \\ & + FE \frac{\beta e^{-\beta L}}{E_o} \left[-\frac{A_1}{q + \beta} (1 - e^{(\beta+q)L}) + \frac{B_1}{q - \beta} (1 - e^{(\beta-q)L}) \right. \\ & \left. - \frac{E_o}{\alpha + \beta} (1 - e^{(\beta+\alpha)L}) \right] \quad (2-25)\end{aligned}$$

The last paper in the final list of selected papers that deals with semi-transparent materials is a paper written by Exarchos et al. [136] The paper deals with a non-destructive technique based on near-infrared (NIR) imaging to assess transparent and semi-transparent composite materials. It introduces the NIR double-transmission mode (NIR-DTM) composed of an NIR sensor, an illumination source, and a reflector surface behind the samples under inspection, which, in this case, were GFRP samples. The technique in this configuration provided a higher spatial resolution of the defect and allowed for a more accurate estimation of the defect size compared to the NIR in the reflection mode.

As mentioned in the previous subsection, the most commonly used techniques used to thermally excite the specimen are flash lamps, eddy current coils, laser pulse, and halogen lamps. The papers that have used pulsed thermography as the thermal excitation method use a description similar to what is explained by Parker et al. [12]. Parker describes the flash as an instantaneous heat source that, when applied to a specimen, heat is “instantaneously and uniformly absorbed in the small depth g at the front surface $x = 0 \dots$ ”. The flash is defined as a Dirac pulse with an energy q_0 . A Dirac pulse is a pulse that has values of zero everywhere except at time zero. It is also known as a unit impulse. Another thermal excitation method is the pulsed eddy current method, which delivers the same pulse of energy to heat up the specimen but with the use of an eddy current coil instead of flash lamps. The articles that have used eddy current heating as

the excitation source describe the physical phenomena in three subcategories. These are eddy current induction, Joule heating, and heat conduction. The first is the eddy current induction, where eddy currents are induced into a material by bringing a current-carrying coil to a conducting material. This induces a localised current perpendicular to the coil's orientation, known as an eddy current. These eddy currents have a penetration depth, which is governed by the following relationship [78]:

$$\delta = \frac{1}{\sqrt{\pi\mu\sigma f}} \quad (2-26)$$

where δ (m) is the depth, f (Hz) is the excitation frequency, σ is the electrical conductivity in S/m, μ is the magnetic permeability in H/m. The heating phenomenon is known as Joule heating, which is caused by eddy current-induced resistive heating. The heat, Q , is related to the eddy current density, J , or the electric field intensity vector, E , by the relation shown in the equation below:

$$Q = \frac{1}{\sigma} |J|^2 = \frac{1}{\sigma} |\sigma E|^2 \quad (2-27)$$

Finally, the heat conduction from a Joule heating source, Q , is governed by the following relation:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla(k \nabla T) = Q \quad (2-28)$$

where the density, specific heat capacity, and thermal conductivity are denoted by ρ (kg/m³), C_p (J/kgK), and k (W/mK), respectively. It has also been determined that for pulsed excitation, the thermal penetration depth is dependent on the thermal diffusivity of the material α as shown in the equation below:

$$\delta_{th} = \sqrt{\frac{\alpha t}{\pi}} \quad (2-29)$$

By observing Equations (2-26) and (2-29), it can be concluded that defect detection using pulsed eddy current thermography is governed by the skin depth and the thermal penetration depth. These two quantities are dependent on the

material's conductivity, permeability, thermal diffusivity, and the material observation time.

Another thermal excitation source for pulsed thermography literature was a laser pulse. Similar to a flash produced by lamps, the laser pulse is characterised by the same Dirac pulse; however, the beam is more concentrated at a certain point on the specimen.

Finally, halogen lamps have also been used in the selected papers that deal with lock-in or frequency-modulated thermography for material characterisation. The halogen lamps thermally excite the specimen by using a thermal wave with a fixed frequency value. Equations (2-30)–(2-34) [123] describe the resulting thermal behaviour induced by the halogen lamps. The first assumption made here is that the thermal wave generated is harmonic in nature and thus can be described by the following heat equation:

$$\frac{1}{\alpha} \frac{\partial}{\partial t} T - \Delta T = \frac{g}{k} \quad (2-30)$$

where k is the thermal conductivity, g is the volumetric heat rate (W), and α is the thermal diffusivity. Thermal diffusivity is also defined as $\alpha = \frac{k}{\rho c_p}$, where c_p (J/kgK) is the specific heat capacity of the material. For a material that is isotropic and homogeneous, the problem can be reduced to a 1D problem, provided that the thickness of sample d is much greater than the thermal diffusion length $\mu = \sqrt{\frac{\alpha}{\pi \cdot f}}$ at the corresponding frequency of the lock-in thermal wave. The temperature within the semi-infinite body can be determined using the angular frequency $\omega = 2\pi f$, as shown in the equation below:

$$T(d, t) = \frac{A}{d} e^{-\frac{d}{\mu}} e^{i(\omega t - \frac{d}{\mu})} \quad (2-31)$$

The phase delay ϕ_{wave} on the back surface can be expressed as:

$$\phi_{wave} = \frac{d}{\mu} \quad (2-32)$$

variable b is defined as:

$$b = d \sqrt{\frac{\pi}{\alpha}} \quad (2-33)$$

The phase delay of thermal wave ϕ at the back side of the sample can be defined using the phase of the thermal wave along with the system-dependent phase delay as follows:

$$\phi = \phi_{system} - \frac{d}{\mu} = \phi_{system} - d \sqrt{\frac{\pi}{\alpha}} \cdot \sqrt{f} = \phi_{system} - b \cdot \sqrt{f} \quad (2-34)$$

the thermal diffusivity is determined by applying a curve fitting based on Equation (2-34).

2.3.2.3 Data Processing Algorithms

The next element for the qualitative analysis is the data processing algorithms. As mentioned in earlier sections, raw thermal images may contain a lot of noise, which requires processing to filter out. For defect detection, several algorithms have been used. Table 2-8 provides a summary of these algorithms and their corresponding equation numbers.

Table 2-8 Most common signal processing techniques for through-transmission

Algorithm	Author and Reference	Equations
Pulsed Phase Thermography	Maldague and Marinetti [43]	(2-35),(2-36)
Principal Component Thermography (PCT)	Rajic [151]	(38)
Thermal Wave Radar Analysis (TWR)	Tabatabaei and Mandelis [152]	(39)–(42)
Diffusion-Compensated Correlation Analysis (DCCA)	Hedayatrasa et al. [110]	(43)–(47)

2.3.2.3.1 Pulsed Phase Thermography (PPT)

Pulsed Phase Thermography (PPT) is a technique first introduced by Maldague and Marinetti [43]. This method converts the obtained thermographic data from the time domain to the frequency domain using the Fast Fourier Transform (FFT). This conversion offers several advantages, such as solving the issues incurred

during data capture, such as non-uniform heating, irregular surfaces, and environmental reflections [153]]. The conversion of each pixel from the time to the frequency domain and the following extraction of the amplitude and phase is conducted via the equations below [43]

$$F_n = \sum_{k=0}^{N-1} T(k) e^{\frac{2\pi i k n}{N}} = Re_n + i Im_n \quad (2-35)$$

$$A_n = \sqrt{Re_n^2 + Im_n^2} \text{ and } \phi_n = a \tan \frac{Im_n}{Re_n} \quad (2-36)$$

where Re and Im are used to obtain the amplitude A_n and phase angle ϕ_n in Equation (2-36). Furthermore, information on the defect depth can be extracted by equating it to the blind frequency, i.e., the frequency where the defect becomes invisible, using the following relation:

$$d = C_1 \sqrt{\frac{\alpha}{\pi f_b}} \quad (2-37)$$

where the correlation constant C_1 has values in the range of 1.5 and 2 [154].

2.3.2.3.2 Principal Component Thermography (PCT)

Principal Component Thermography (PCT), introduced by Rajic [151], is a signal processing technique that makes use of single-value decomposition to distinguish undesirable data from an image while retaining its major features. It reduces the temporal and spatial thermal data from three dimensions to two. The input thermal image is then reconstructed from a matrix in which each single image pixel has a raster-like arrangement on each row. This way, each column represents the temporal evolution of a specific pixel. Using Empirical Orthogonal Function (EOF) analysis, a matrix A is created with $M \times N$ dimensions, which can be decomposed as follows [151]:

$$A = USV^T \quad (2-38)$$

where the spatial variation is represented through the orthogonal matrix U that has dimensions $M \times N$ and a set of EOFs. S is also a matrix of $M \times N$ dimensions

containing the singular values of matrix A on the diagonals. The transpose of the orthogonal $N \times N$ matrix that represents characteristic time is denoted by V^T .

2.3.2.3.3 Thermal Wave Radar Analysis (TWR)

Thermal Wave Radar Analysis [152], first introduced by Tabatabaei and Mandelis, is a subsurface imaging modality that draws from linear frequency-modulated continuous wave radars and frequency domain Photothermal Radiometry (PTR). It was specifically designed to enhance the depth resolution of subsurface defects. To calculate the TWR amplitude (CC), the following equation is used [152]:

$$CC(\tau) = F^{-1}\{\text{REF}(\omega) * S(\omega)\} \quad (2-39)$$

where $\text{REF}(\omega)$ is the Fourier transform of a reference non-defective pixel $\text{ref}(t)$, and $S(\omega)$ is the Fourier transform of pixel $s(t)$. The symbol $*$ denotes the complex conjugation. The inverse Fourier transform and the time delay between $\text{ref}(t)$ and $s(t)$ are denoted by F^{-1} and τ , respectively. ΔCC , which is the differential TWR CC, is calculated as shown in Equation (2-40):

$$\Delta CC(\tau) = CC(\tau) - CC_{ref}(\tau) \quad (2-40)$$

The object temperature and emissivity strongly affect the TWR amplitude (CC). Equation (2-41) can be used to calculate the TWR phase (θ).

$$\theta(\tau) = \frac{F^{-1}\{\text{REF}(\omega) * S(\omega)\}}{F^{-1}\{[-i \text{sgn}(\omega) \text{REF}(\omega)] * S(\omega)\}} \quad (2-41)$$

where $\text{sgn}(\omega)$ is defined as the signum function and i is the imaginary component. The phase θ is independent of the emissivity and dependent on the time-delay quantity. The TWR phase differential is calculated by the following equation:

$$\Delta \theta(\tau) = \theta(\tau) - \theta_{ref}(\tau) \quad (2-42)$$

where $\theta_{ref}(\tau)$ is the reference TWR phase resulting from non-defective pixels. $\Delta \theta(\tau)$, like $\theta(\tau)$, is an emissivity-independent and time-delay-dependent quantity.

2.3.2.3.4 Diffusion-Compensated Correlation Analysis (DCCA)

DCCA relies on analysing the correlation between the thermal response and a collection of template thermal responses that have been calculated analytically. Equation (5) in [110] is used to compute a depth library $\psi_d(d, t) = \psi(d, \alpha = \alpha_r, t)$. This results in a 2D array of size $[N_d, N_s]$ that includes N_d depth components calculated for N_s time components based on a known thermal diffusivity value α_r . This identifies the highest similarity between the measured and template response and the corresponding depth. The analytical library is standardised with respect to the temporal Root Mean Square (RMS), as the form and magnitude of the analytically computed thermal responses vary largely by depth and, therefore, cannot be used as a meaningful measure of similarity [110].

$$\psi_{d,std}(d_m, t_n) = \frac{\psi_d(d_m, t_n)}{\sqrt{\frac{1}{N_s} \sum_{i=1}^{N_s} \psi_d^2(d_m, t_i)}}, \begin{matrix} m \in \{1, 2, 3, \dots, N_d\} \\ n \in \{1, 2, 3, \dots, N_s\} \end{matrix} \quad (2-43)$$

Seeking out the component that exhibits no lag time, i.e., $\tau = 0$, is an effective strategy when there is a lack of synchronization between the excitation system and the acquisition system. For a synchronised system, it is better to seek the maximum magnitude at 0 lag time. This can be effectively determined through a singular correlation analysis of the time response throughout the depth dimension of the library.

$$\mathbb{C}_d(d_m) = \frac{1}{N_s} \sum_{i=1}^{N_s} \psi_{d,std}(d_m, t_i) T_{std}(t_i), m \in \{1, 2, 3, \dots, N_d\} \quad (2-44)$$

where T_{std} is the standardised thermal response with respect to its RMS value:

$$T_{std}(t_n) = \frac{T(t_n)}{\sqrt{\frac{1}{N_s} \sum_{i=1}^{N_s} T^2(i)}}, n \in \{1, 2, 3, \dots, N_s\} \quad (2-45)$$

Obtaining the estimated depth $\hat{d}$ of the measured response, the peak $\mathbb{C}_d$ and the corresponding depth is found using the following relation:

$$Peak_{\mathbb{C}_d} = \underset{m}{\operatorname{argmax}}(\mathbb{C}_d(d_m)) \quad (2-46)$$

$$\hat{d} = d_m |_{\mathbb{C}_d(d_m)=Peak_{\mathbb{C}_d}} \quad (2-47)$$

2.3.2.4 Data Analysis

The data analysis element in the qualitative analysis evaluates the paper's presentation and interpretation of the data. Thermography is primarily a visual-based inspection technique, which is why papers have conducted simulations or experiments and presented the resulting thermograms. The studies that have conducted signal reconstruction using either novel or existing techniques have also completed a comparative analysis to either validate their findings based on existing literature or to prove that their proposed method is superior [57,78,135,144,151]. Furthermore, since the presence of a defect is identified by observing a deviation in the time vs. temperature curve between defect and defect-free zones, most of the results have been presented in the form of graphs that represent this change. Verification of the findings has been conducted via several means, such as an uncertainty analysis, as shown in [106,110], that uses relative standard deviation as an indicator of measurement uncertainty. Others include different types of statistical analysis that indicate precision, repeatability, or both [87,115]. For defect depth prediction, samples of known defect depths are inspected, and the predicted values are validated by comparing them with the real values, as seen in [119]. Other studies on defect detection present the defect detection limit with little or no information on measurement uncertainty, such as in [6,124].

2.3.2.5 Conclusion and Future Work

This part of the qualitative analysis focuses on how the authors of the selected papers concluded their papers. This includes the limitations of their work and what could be done to improve it by proposing prospective future work. Out of the 81 selected papers, 25 of them either offered an indication or explicitly mentioned/proposed future works following their findings. Eleven papers commented purely on the limitations of the work. Six papers explicitly listed their contribution to knowledge, and two papers contained a direct comparison of their proposed methodology to existing techniques. The remaining papers provide a

summary of the study and re-iterate the fact that their proposed methods can successfully deliver the desired outcome.

2.4 Research Outcomes

In Section 2.2.2, three key research questions were formulated to refine the search scope and maintain the systematic nature of this review. The purpose of this section is to provide answers to these questions based on the final selection of papers.

1. The first research question was, “How effectively can through-transmission thermography evaluate thermal material properties?” Through-transmission thermography has demonstrated that it can effectively determine thermal diffusivity. Commercial instruments such as the Netzsch LFA measure thermal diffusivity using pulsed thermography in the transmission configuration. Thermal diffusivity measurements have been taken using other active methods, such as lock-in thermography. Moreover, the technique has also been used to detect the thermal properties of different materials, such as cellulose fibres [102], spider silk [112], and other various microfibers [6].
2. Regarding the second question, “What are the fundamentals (definition, working principle, application) and the current state-of-the-art in through-transmission thermography for material and defect characterisation?” Through-transmission thermography is defined by the positioning of the infrared radiometer and the heat source relative to the specimen. In through-transmission thermography, the heat source and the IR radiometer are placed on opposite sides of the specimen. Therefore, through-transmission thermography is also sometimes referred to as “two-sided testing” [149]. It is also important to note that the definition of through-transmission can have various heat sources, as shown in Section 2.3.2.2, where the working principles of different heat sources are explained. From the literature search, it can also be concluded that heat sources which have longer heating times, such as in frequency-modulated thermography, are the preferred choice when depth information for the

defect is required. This could be attributed to the frequency-dependent nature of the thermal wave. The frequency value could be changed to determine the depth of the defect. The working principle of through-transmission is based on the heat diffusion theory. When a specimen is excited from one end, heat will diffuse through the material, causing a temperature rise on the back wall. While heat can travel in all three directions, through-transmission thermography focuses on one-dimensional heat transfer, which is the direction of the samples through thickness. The amount of temperature rise on the back wall is dependent on the thermal diffusivity of the material, which itself is dependent on a material's thermal conductivity, density, and specific heat capacity. The greater the value of thermal diffusivity, the greater the rate at which temperature increases at the back wall. However, as mentioned before, heat travels in all three directions; hence, the heat intensity is reduced in the through-thickness direction as it goes through. For materials that contain defects, the literature has shown that these are in the form of an airgap, such as when a material goes through corrosion, which results in sample thinning. This means that the heat has less distance to travel in the direction of thickness, resulting in less heat dissipation in the other two directions, resulting in a localised hotspot. If the air gap is a subsurface between the front and the back wall of the sample, that will result in a cold spot at the location of the defect, as the heat will take longer to diffuse through the material since the thermal conductivity of air is less than metals and composites. In terms of theoretical models for through-transmission, all of the papers using pulsed thermography adopt Parker's model to calculate the thermal properties of the material with the exception of [87]. The current state-of-the-art in through-transmission thermography is tilted more towards the signal reconstruction algorithms rather than the physics behind the technique. To enhance the image obtained from raw thermographs, various signal reconstruction algorithms such as pulsed phased thermography, principal component and independent component analysis, wavelet transform, and thermal wave radar analysis are used.

Thermal diffusivity measurements are also conducted using the same equation, although one study developed a novel method for computing thermal diffusivity by accounting for the heat losses in the front and rear surfaces [87]. In terms of technique development, work has been conducted on the positioning of temperature probes to calculate thermal diffusivity more accurately [95].

3. Lastly, the third and final research question was, “What advantages and/or limitations does the transmission mode have in terms of defect and material characterisation compared to the reflection mode?” Limited studies have answered this question, but it has been observed that the transmission mode is able to detect subsurface defects with better spatial resolution, as shown in [4]; however, no reason is provided as to why this happens. Based on the author’s knowledge, there are several reasons why the reflection mode is able to detect shallow defects only. One of the reasons is the physical limitation of the reflection mode. This can be explained by assuming a sample with no defects. While the temperature decay curve will flatten out after some time, as shown in [113], this characteristic time can be used to compute the length of the sample. However, for components with a greater thickness value, by the time the heat reaches the back wall, the signal-to-noise ratio is reduced to the point where detecting temporal anomalies is no longer possible. This reduction in the signal can be attributed to the heat capacitance of the material, where the heat is stored within the material rather than diffusing through its thickness. Moreover, one-dimensional heat transfer is considered, but in reality, heat is flowing in three directions, further reducing the heat propagation through the sample’s thickness. For the transmission mode, this limitation does not exist, as the temperature increase is observed from the back wall. Other limitations could be the camera itself, its sensor integration time, and the frame rate for data acquisition, in which case it misses the event at which the temperature change due to a defect occurs. Finally, there are limitations with the signal reconstruction algorithms themselves, whether they are powerful enough to enhance the raw

thermograms for defect detection. The last two limitations could be attributed to both reflection and transmission modes; however, existing literature has indicated the potential for through-transmission thermography to be a better choice for subsurface defect detection and characterisation.

2.5 Conclusion and Outlook

The primary motivation for conducting this state-of-the-art review was to generate greater interest in thermography in the transmission mode by presenting the current state-of-the-art and highlighting its potential in defect characterisation. This revealed the untapped areas of research for this technique. With the increased use of materials, such as CFRPs, in various industries, as discussed in [4], the need for a reliable NDT technique to effectively assess the structural integrity of these structures is paramount. While the reflection mode in thermography does exist for this purpose, its limitations in depth and lateral resolution adversely affect its capabilities in thermal material property evaluation. Currently, the limitation of the through-transmission technique within the context of pulsed thermography lies in the depth of quantification of defects. The reason provided for this is the fact that in the two-sided testing, the distance travelled by the thermal wave in the defect and defect-free region is the same [8]. Another explanation that was recently presented showed that the temperature contrast between the defect and defect-free zones is not sensitive to defect depth [142]. Besides this, theoretical models provide an in-depth knowledge of the thermal behaviour in the transmission mode to understand why depth quantification is a challenge that is currently lacking in the literature. Moreover, the literature survey also reveals that there is no standard procedure to conduct thermographic measurements in the transmission mode, for example, in terms of the optimal distance of the IR radiometer to the sample or an uncertainty analysis using various excitation energy levels in determining the thermal diffusivity. This also includes exploring the effect of thermal diffusivity calculations for the same material at varying thicknesses. While thermal diffusivity is an intrinsic material property, i.e., its value does not change with changing size; practical scenarios

could show slight variations that need to be considered when evaluating thermal material properties. Lastly, to ensure repeatability, multiple runs should be conducted under the same experimental conditions. While some of the papers included in this literature review may have conducted multiple runs, greater transparency in reporting this procedure would strengthen their findings. This can be achieved through an Analysis of Variance (ANOVA) (see Chapter 3), which statistically assesses whether the variation between repeats is significant. ANOVA assumes that the data within each group follow a normal distribution, an important consideration as it ensures that the test results are valid and comparable. Demonstrating that the residuals are normally distributed allows for more reliable interpretation of the statistical significance, thereby enhancing the transparency and credibility of the reported results. Therefore, it is recommended that a thorough analysis of through-transmission thermography be conducted, considering all the mentioned variables in the determination of thermal material properties. This will allow for a standardised and transparent method of thermographic inspections in the transmission mode. If these limitations can be overcome, it would provide a more reliable tool for the NDT industry to characterise defects. Applications include but are not limited to predictive maintenance, where the remaining useful life of components can be estimated for different types of defects with greater accuracy. While other techniques exist, such as lock-in and vibrothermography, it must be noted that the inspection time is longer as a good understanding of the techniques' response to excitation frequency is required beforehand, thereby reducing the overall reliability to detect all types of defects. Furthermore, it would also provide better insights into the true limitations of pulsed thermography, since existing challenges, such as defect depth information extraction, could potentially be overcome by integrating the inspection with technologies central to Industry 4.0, such as artificial intelligence (AI) for advanced signal processing, digital twins for predictive modelling, machine learning for automated defect classification, and the Industrial Internet of Things (IIoT) for real-time data acquisition and analysis.

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acquisition; Zhao, Y review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

3 Thermal Diffusivity estimation

Effective Thermal Diffusivity Measurement Using Through-Transmission Pulsed Thermography: Extending the Current Practice by Incorporating Multi-Parameter Optimisation

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Abstract

Through-transmission pulsed thermography (PT) is an effective non-destructive testing (NDT) technique for assessing material thermal diffusivity. However, the current literature indicates that the technique has lagged behind the reflection mode in terms of technique development despite it offering better defect resolution and the detection of deeper subsurface defects. Existing thermal diffusivity measurement systems require costly setups, including temperature-controlled chambers, multiple calibrations, and strict sample size requirements. This study presents a simple and repeatable methodology for determining thermal diffusivity in a laboratory setting using the through-transmission approach by incorporating both finite element analysis (FEA) and laboratory experiments. A full-factorial design of experiments (DOE) was implemented to determine the optimum flash energy and sample thickness for a reliable estimation of thermal diffusivity. The thermal diffusivity is estimated using the already established Parker's half-rise equation and the recently developed new least squares fitting (NLSF) algorithm. The latter not only estimates thermal diffusivity but also provides estimates for the input flash energy, reflection coefficient, and the time delay in data capture following the flash event. The results show that the NLSF is less susceptible to noise and offers more repeatable values for thermal diffusivity measurements compared to Parker, thereby establishing it as a more efficient and reliable technique.

Keywords

infrared thermography; through–transmission; thermal diffusivity; full-factorial design; finite element analysis; pulsed thermography

3.1 Introduction

Industry 4.0 is characterised by the advancement of various technologies such as the connectivity of computer systems, the Internet of Things (IoT), Big Data, Smart Factories, autonomous robots, predictive maintenance, and Additive Manufacturing. In the context of the non-destructive testing (NDT) sector, this translates into changes in inspection procedures driven by the progression of Industry 4.0 [28]. Traditionally, NDT is a manual procedure conducted to ascertain a material's structural integrity in the presence of defects and damage. Advancements in technologies such as machine learning and deep learning have become a key aspect in interpreting complicated inspection data to achieve higher levels of detectability and overall efficiency of defect detection [30]. NDT offers a wide range of inspection technologies operating on a set of physical principles that determine structural anomalies within a component [30]. For example, ultrasonic testing, or UT, is a popular NDT technique that uses guided ultrasonic waves to locate and evaluate potential flaws. However, every NDT technique has its limitations. Some, such as X-ray inspection, rely on radiative methods, raising safety concerns, while others require the application of additional materials, such as water, gels, or magnetic particles, making them unsuitable for certain inspection scenarios. Infrared Thermography (IRT) has emerged as a non-contact, non-intrusive technique that overcomes many of these challenges, offering an alternative for defect detection [155].

The last two decades have seen rapid advancements in various IRT technologies to assess materials that are used for a wide range of applications. Pulsed thermography (PT), a subset of IRT, is a robust technique, making it an attractive solution to assess metals and composites [156,157]. A range of PT applications can be found in industries such as automotive, aerospace, defence, and oil and gas [4,39,158,159]. PT measurements can be taken in two modes: reflection and

transmission. The key difference between these modes is the placement of the heat source and the IR radiometer with respect to the component under inspection. The reflection mode has both the radiometer, and the heat source placed on the same side of the specimen, and the transmission mode has the heat source and radiometer placed on opposite sides.

A limitation of the reflection mode is that it loses its reliability in estimating thermal diffusivity when the thickness of a sample is over 3 mm [4]. This is problematic, as accurately determining the property is essential for evaluating the material's structural integrity. Thermal diffusivity governs how quickly heat can diffuse through a material due to an induced temperature difference at the surface of a material. To combat this issue, multiple signal processing algorithms can be used, such as Thermographic Signal Reconstruction [160], Pulsed Phased Thermography [43], Principal Component Thermography [151], Differential Absolute Contrast [161], Absolute Peak Slope Time [162], and Nonlinear System Identification [163]. Furthermore, keeping in line with the rapid progression of technologies in Industry 4.0, various AI technologies have been developed, such as for-ward-feeding neural networks and deep neural networks, to identify and classify defects caused by different environmental effects [39,131,150,164]. One other technique that has shown potential in accurately measuring thermal diffusivity is the through-transmission technique. Due to its higher levels of reliability, it has been commercialised into systems such as the Netzsch Laser Flash Apparatus (LFA) [150].

The literature shows that the primary motivation for developing PT is to enhance its defect characterisation capabilities. The introduction of a defect within a material, such as an air gap, results in a time delay for heat propagation through its thickness due to the significantly lower thermal conductivity of air. This thermal delay translates into a localised hotspot which can be utilised to identify and characterise a defect. For PT, the majority of the research has been focused solely on the reflection mode [14]. A major reason for this is the transmission mode's inability to quantify defect depth despite offering greater lateral resolution for defects and the ability to detect deeper subsurface defects when compared

to the reflection mode, as demonstrated by Maierhofer et al. [4]. This has prompted researchers to refocus their efforts solely on the defect detection capabilities of through-transmission thermography by exploring the 2-D spatial distribution of thermal diffusivity [165]. However, a recent review indicated that while the technique has a lot of potential, it has not been explored as much as the reflection mode [14]. A plausible explanation for this is attributed to the fact that for the transmission mode, the distance travelled by the thermal waves in both the defect and defect-free zones is the same [8]. However, this explanation provides limited evidence mathematically or theoretically to support the claim. A previous study attempted to provide a more in-depth analysis to address this knowledge gap by developing a finite element model using COMSOL (v.6.0) [142]. The paper implemented a Taguchi Design to analyse the thermal contrast, i.e., the temperature difference between the sound and defect areas. It was concluded that the peak thermal contrast is more sensitive to defect size than depth. Furthermore, it was determined that the signal-to-noise ratio (SNR) is less sensitive to defect depth when compared to the reflection mode [142]. However, after a certain depth, as the defect moves closer to the back surface, the transmission mode offers a better SNR compared to the reflection mode [14].

Whilst there have been numerous studies that explore the effect of different input parameters on the detectability of defects [166–170], they lack a comprehensive illustration of their influence on the defect detection limits. Only recently, a comprehensive study was published that explored the defect detection limits using a wide range of inspection conditions [171]. However, this study illustrated the limitations of the reflection mode exclusively using a simulation environment. This was due to the extensive nature of the study, which would take years to replicate physically. The present literature continues to show a lack of studies exploring the capabilities of the transmission mode in defect detection, even though it is a well-established technique for determining the thermal diffusivity of various materials [12,80,90,103]. Furthermore, research also shows a lack of studies employing techniques such as factorial designs to understand the interaction of multiple variables in the calculation of thermal material properties such as thermal diffusivity. It must be understood that material thermal diffusivity

is an intrinsic property of any given material and does not change with its geometry. However, it has been demonstrated previously that practical measurements will adversely affect the measurement uncertainty in the thermal diffusivity measurement for the same material when input variables such as sample thickness and flash energy are varied [172,173].

Previous work has highlighted the existing limitations of active thermography [14], particularly the absence of theoretical models that simulate PT in transmission mode. Moreover, it showed that the existing literature does not contain a simple step-by-step procedure for conducting through-transmission inspections. This study aims to address these two issues to help mitigate some of the existing challenges hindering the advancement of through-transmission [14]. Here, the effect of varying thicknesses and flash energy levels in thermal diffusivity evaluation of a defect-free sample is analysed. These variables were chosen due to their well-documented influence on thermal diffusivity estimation, as mentioned above. Furthermore, they are fundamental to the technique and relatively straight-forward to manipulate in controlled experiments: flash energy determines the heat input to the sample, while sample thickness governs the thermal response dynamics and heat propagation, both of which directly impact the thermal response signal critical for diffusivity estimation. In contrast, factors such as environmental conditions (e.g., ambient temperature and air currents), sensor characteristics (e.g., quantisation and noise), and system calibration are more challenging to control or to vary systematically, often introducing confounding effects that complicate the analysis. Moreover, in laboratory settings, the environment is relatively consistent; therefore, its effect on thermal diffusivity estimation is negligible. Consequently, flash energy and sample thickness offer a practical and precise framework for investigating the effects on thermal diffusivity estimation. Also, previous research has identified these two factors as the most influential in accurately assessing thermal diffusivity [173]. Moreover, this study also seeks to update the current established practice of thermal diffusivity estimation by incorporating multi-parameter optimisation. Additionally, the sensitivity of the camera standoff distance to the sample in evaluating thermal diffusivity is also investigated. Since there are only two variables that are being

manipulated (sample thickness and flash energy level), a full-factorial design of experiments (DOE) is considered. The justification for using this type of DOE compared to other more practical design of experiment methods, such as Taguchi design, is because a full-factorial DOE offers a more comprehensive understanding of the interaction of multiple parameters on the output. Moreover, Taguchi is preferred when there are multiple input parameters leading to a large set of experimental runs. However, the number of runs in this study is not high enough to render the full-factorial design impractical.

The intended outcome of this research is to provide a standardised approach to measuring thermal diffusivity using flash thermography in the through-transmission configuration. While commercial apparatus such as the Netzsch LFA exist, they are expensive due to the inclusion of temperature-controlled chambers and the need for multiple calibrations. Furthermore, they often require samples to be of specific dimensions for measurement. The setup in this paper will provide a simple and more cost-friendly alternative that can be replicated in laboratory settings. The novelty of this paper lies in its assessment of the viability of thermal diffusivity measurement using PT in the through-transmission configuration using multi-parameter optimisation together with Parker's half-rise equation, providing a comprehensive understanding of all the parameters that have an impact on the measurement (See Section 4.3.4 for more details). Further-more, the scope of this research aligns with identifying the applicability of the through-transmission technique for assessing advanced materials used in fields such as additive manufacturing by providing a turnkey solution.

3.2 Theory

This section discusses the fundamental theory that governs heat transfer in a material. It is critical that the fundamental theory be fully understood to appreciate the strength of the through-transmission technique, something that has not been extensively documented by researchers. Based on this, the equations governing the front and back wall temporal behaviour of a sample exposed to pulsed heating are derived. From those equations, the thermal diffusivity of any material can be measured.

3.2.1 Pulsed Thermography (PT)

For PT, the heat source comprises either a laser source or flash lamps that deliver an instantaneous pulse of heat lasting in the order of milliseconds. The applied heat is absorbed by the specimen's surface, thereby increasing its temperature. The theory of heat diffusion follows the classical heat diffusion equation, also known as the Fourier equation, which is as follows:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (3-1)$$

where $\alpha = \frac{k}{\rho C}$ is the thermal diffusivity of the material (m^2/s), k is the thermal conductivity (W/mK), ρ is the density (kg/m^3), C is the specific heat (J/kg K), T is the temperature (K), and t is the time (s). Fourier's law of heat conduction states that the rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. Since the heat is applied at the front surface, the negative temperature gradient is highest in the thickness direction, making it the dominant direction in which heat flows. Moreover, the lateral dimensions of the sample are significantly larger than the thickness, resulting in negligible negative temperature gradients along those directions despite the isotropic nature of thermal properties in homogeneous materials. This reduces the three-dimensional heat transfer problem to a one-dimensional heat flow, allowing Equation (3-1) to be simplified as follows:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (3-2)$$

where x is the direction parallel to the through thickness of the material. While there are numerous solutions for the equation above with different boundary conditions, a popular solution was determined by Carslaw and Jaeger [65]. The equation assumes a semi-infinite plate that is thermally insulated. The initial temperature is defined as $T(x, 0)$, and the temperature later on at any given time t can be defined as follows:

$$T(x, t) = \frac{1}{L} \int_0^L T(x, 0) dx + \frac{2}{L} \sum_{n=0}^{\infty} e^{\left(\frac{-n^2 \pi^2 \alpha t}{L^2}\right)} \times \cos\left(\frac{n \pi x}{L}\right) \int_0^L \frac{T(x, 0) \cos n \pi x}{L} dx \quad (3-3)$$

Parker et al. [12] took the solution derived by Carslaw and Jaeger and added specific conditions to overcome two key challenges to solving Equation (3-3). First, the thermal contact resistance between the sample and the heat source is eliminated by introducing flash excitation. Second, the data capture time is reduced to the point where surface heat losses can be avoided. Applying these conditions, for a semi-infinite plate with length L subjected to a Dirac pulse of energy value Q , the temporal evolution of the front and back walls can be calculated using the following equations. For the front wall:

$$T(0, t) = \frac{Q}{\rho C L} \left[1 + 2 \sum_{n=0}^{\infty} \exp\left(-n^2 \pi^2 \frac{\alpha t}{L^2}\right) \right] \quad (3-4)$$

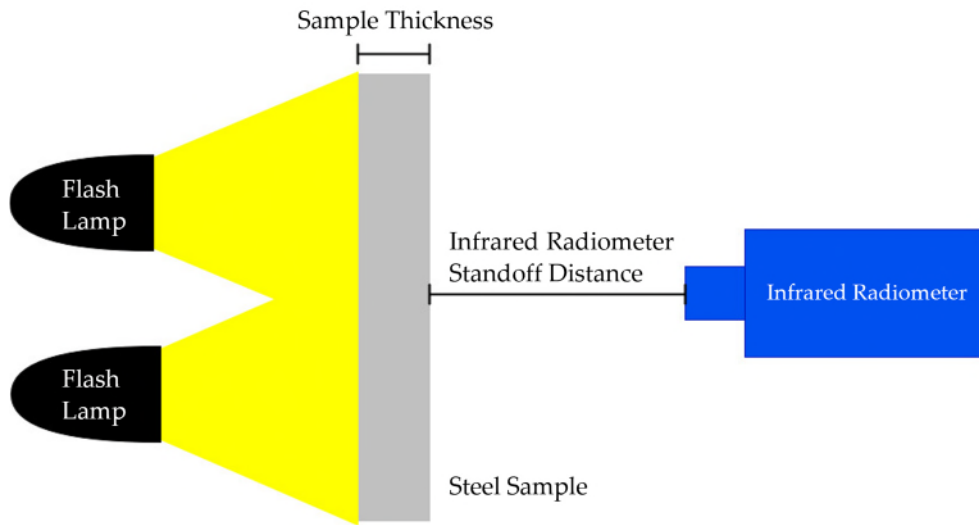
And for the backwall

$$T(L, t) = \frac{Q}{\rho C L} \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp\left(-n^2 \pi^2 \frac{\alpha t}{L^2}\right) \right] \quad (3-5)$$

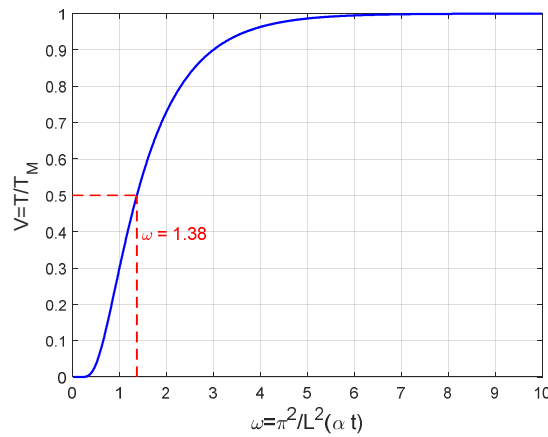
where ρ is the density (kg/m³), C is the material's specific heat capacity (J/kg K), and α is the material's thermal diffusivity (m²/s). The equations above can be made dimensionless to make the relation between temperature and time independent of material properties. This is done by introducing two dimensionless parameters. The first parameter is $V = \frac{T}{T_M}$, where V is the ratio of the temperature T to the maximum temperature T_M , and the second is $\omega = \frac{\pi^2 \alpha t}{L^2}$, the dimensionless time quantity. Using this relation, Equation (3-5) is then reduced to the following:

$$V(L, t) = \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp(-n^2 \omega) \right] \quad (3-6)$$

For the front wall, Equation (3-6) remains the same as the front wall Equation (3-4) but with the inclusion of the term $(-1)^n$ to indicate the direction of heat flow in the 1-D model. That term refers to the phase inversion of the thermal wave that has reflected off an adiabatic wall at the back causing a temperature rise. Figure 3-1 presents a schematic representation of the through-transmission configuration with its respective back wall temperature curve based on Equation (3-6). Note that since V and ω are dimensionless quantities, the axis labels do not contain any units.



(a)



(b)

Figure 3-1 (a) Illustration of the PT transmission mode configuration; (b) nondimensionalised back wall temperature plot displaying the value for ω at half the maximum temperature.

As seen in Figure 3-1a, the flash lamps are used to thermally excite the specimen from the front. On the other side, an infrared radiometer is placed at a certain standoff distance (See Section 4.4.2 for details) to record the back wall temperature.

Using the temperature curve at the back wall, Parker et al. determined that when the temperature at the back wall reaches half its maximum temperature, the value of $\omega = 1.38$, as shown by the dotted red lines in Figure 3-1b. If either the sample length or thermal diffusivity is known, the other value can be calculated using the following relationship:

$$\alpha = \frac{1.38 L^2}{\pi^2 t_{\frac{1}{2}}} \quad (3-7)$$

The above method, known as Parker's half-rise equation, has become the gold standard method for measuring thermal material properties using PT and has also been employed by commercially available instruments. The thermal material properties evaluated using this method are for materials that are defect-free. For materials that contain defects such as air gaps, the temperature response will be different in the defect and defect-free zones. These temperature anomalies can be used to characterise the defects. Since these anomalies are caused by local thermal diffusivity variations within the material, it is crucial to establish a simple and repeatable approach that can effectively measure this value.

While other thermographic techniques such as lock-in, frequency-modulated thermography, and step heating exist, PT offers several advantages, such as improved SNR, faster inspection times, and the ability to operate without prior knowledge of specific modulation frequencies [174]. It has also been observed that longer heating times, such as the ones provided by lock-in and step heating, allow for the detection of deeper defects [10,44,149]. Moreover, recent studies have employed novel algorithms such as diffusion-compensated correlation analysis for frequency-modulated thermal signals to further reduce temporal noise, allowing for better defect resolution [110]. Finally, based on the available literature, a comparative study between pulsed thermography (PT) and step-

heating thermography has demonstrated that step heating achieves a higher damage detection efficiency (94% compared to PT's 88%). However, PT provides significantly more accurate defect size estimation, with an average error of 16.64%, whereas step heating results in a much higher average error of 37.73% [44]. This, combined with the previously mentioned advantages of PT, makes it a strong contender for material characterisation and, therefore, is the sole focus of this study.

3.3 Methods and Materials

The purpose of this section is to outline methods and materials used in the study to estimate thermal diffusivity. The methodology is applied to both the finite element analysis (FEA) and the laboratory experiments.

3.3.1 Materials

The samples used for the laboratory experiments are seven 100 mm × 150 mm S275 grade steel plates (thermal diffusivity = 14 mm²/s, based on the material information provided by the supplier) with thickness values ranging from 2.12 mm to 9.87 mm. The entire surface of the steel plates (front and back) is painted black with a matte finish in line with the previous works primarily to reduce sample reflectivity and to ensure that its emissivity values are close to 1 [173,175]. If the sample has low emissivity, the radiation detected by the radiometer will not accurately represent the sample's temperature. While potential solutions to address this issue have been explored in the literature, including those presented by Ruffio et al. [176], they require multiple flashes, which would significantly increase the experimental time. Figure 3-2 shows the back wall temperature plot from Figure 3-1b at different emissivity values by multiplying different emissivity values with the output of Equation (3-6). It can be inferred from the figure that lower emissivity causes the back wall temperature to increase at a slower rate. This occurs because samples with lower emissivity absorb less incidental radiation on their surface and reflect a greater proportion of it.

For the thermal excitation, two optical flash lamps, each lamp providing a maximum excitation energy of 4.8 kJ, are used. A detailed overview of the thermal

excitation values used for the laboratory experiments can be seen in the next subsection of this paper. The lamps are synced with the data acquisition software Research IR and the IR camera so that the frame at which the flash occurs can be recorded. The pulse duration of the lamps can be varied to achieve the required level of energy. According to the manufacturer, it offers 1/175 s at 4.8 kJ, 1/300 s at 2.4 kJ, 1/500 s at 1.2 kJ, 1/900 s at 0.6 kJ, and 1/1425 s at 0.3 kJ. The IR camera used is a FLIR SC7600 mid-wave camera (3–5 μm wavelength range) offering a resolution of 640×512 pixels operating at a frame rate of 100 Hz.

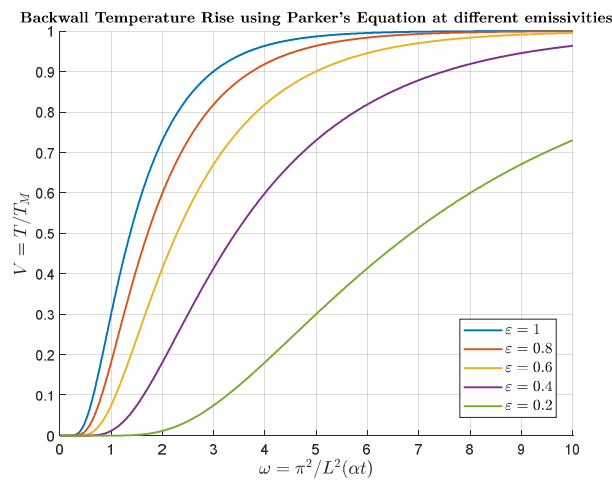


Figure 3-2 Normalised back wall temperature profile at different emissivity values.

3.3.2 Finite Element Modelling

To simulate flash thermography, the “Heat transfer in Solids” physics module available in COMSOL (v.6.0) was used to model a steel plate with dimensions 150×100 mm and varying depth. Figure 3-3 shows the FEA model. To reduce the simulation time, only a small region (highlighted in yellow) is finely meshed. Here, the option of an extremely fine mesh is selected, which is a size preset in COMSOL. The size of the elements used in both the region of interest (extremely fine) and the rest of the geometry (normal) are shown in Table 3-1 (under the heading “Meshing Parameter (area of interest)” and “Meshing Parameter (rest of the geometry)”). The back wall temperature information is extracted by taking a surface average of the yellow region once the simulation is complete. The analysis comprises a parametric sweep that encompassed all the sample

thicknesses at each energy level for a duration of 10 s with a time step of 0.01 s to replicate the rate of acquisition offered by camera FLIR SC7600 IR Camera.

Table 3-1 Input parameters for the FEA analysis.

Thermal material properties	
Specific Heat Capacity (J/kg K)	470
Density (kg/m ³)	7900
Thermal Conductivity (W/m K)	50
Plate Geometry	
Height (mm)	150
Width (mm)	100
Thickness (mm)	2.12, 3.07, 3.86, 4.87, 5.93, 7.78, 9.87
Heat Transfer Physics	
Initial Temperature (K)	293.15 (applied to the entire body)
Pulse Energy (kJ)	9.6, 4.8, 2.4
Pulse Width (s)	1/175, 1/300
Heat Flux q_0 (W/m ²)	$((\text{Pulse Energy}/\text{Pulse Width})/(\text{Width} \times \text{Height})) \times B$ (t)
Convective Heat Transfer Coefficient h (W/m ² K)	5
Emissivity ϵ	0.95
Meshing Parameter (area of interest)	
Mesh Size (uniform in all directions including through thickness)	Extremely Fine
Maximum Element Size (m)	0.001
Minimum Element Size (m)	0.00001
Maximum Element Growth Rate	1.3
Curvature Factor	0.2
Resolution of Narrow Regions	1
Meshing Parameter (rest of the geometry)	
Mesh Size (uniform in all directions including through thickness)	Normal
Maximum Element Size	0.015
Minimum Element Size	0.0027
Maximum Element Growth Rate	1.5

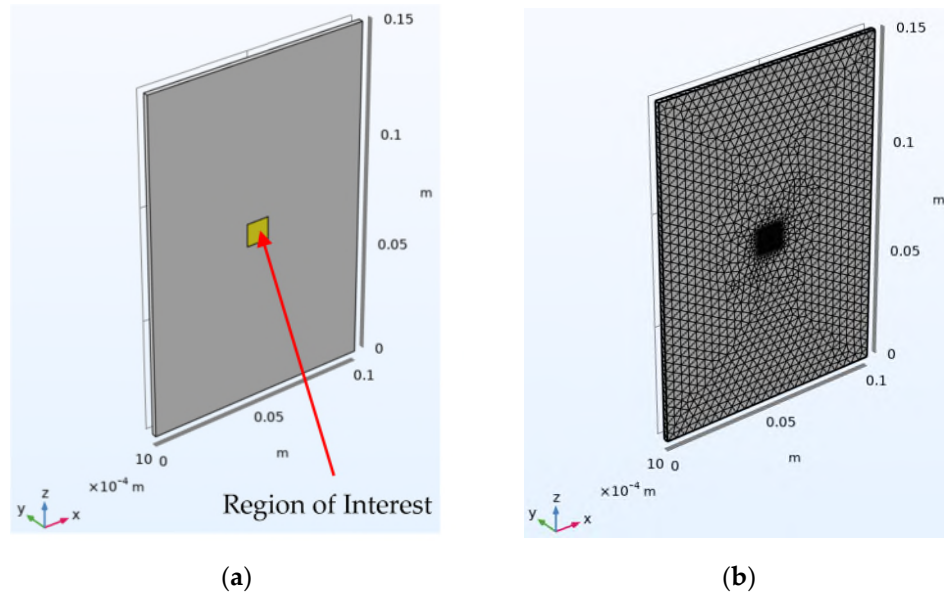


Figure 3-3 Geometry for the FEA Model. (a) The yellow region is where the temperature measurements are taken from at the back wall. (b) The meshed geometry is where the region of interest has a finer geometry to save computational time.

To ensure that the simulations are accurate, all the input parameters, material properties, and dimensions are chosen to be the same as the ones used in the experiments. For the flash heat, a heat flux was applied to the front surface at different energy levels. To control the pulse duration, a pulse function was created that simulates a square pulse $B(t)$. The width of the square pulse is adjusted to set the pulse duration. The flash energy and duration are set to match the experimental conditions. The region of interest is set in the centre of the plate to be consistent with the region of interest selected for the experiments (See Section 4.2). The justification for using the centre of the plate is based on previous work found in the literature that indicates obtaining temperature information from this region provides the most accurate and reliable result [177,178]. Table 3-1 shows the input parameters used in COMSOL. The thermal properties and material geometry are selected in accordance with the steel plates that are used in the experiments. The inspiration for Table 3-1 is drawn from Vora et al. [179]. It is

one of the few papers that outlines the exact input conditions used in COMSOL so that the study can easily be replicated. Since one of the objectives of this paper is to standardise the methodology through which data are collected in the transmission mode, there should be a repeatable approach outlined to do so, as mentioned previously by Ali et al. [14]. This approach should be clearly constructed so that the readers of this research can easily reproduce its contents.

3.3.3 Full-Factorial Design

Full-factorial design of experiments has been a popular choice that allows an investigator to study the effects of multiple input parameters on an output response. A detailed explanation of how to conduct a full-factorial DOE can be found in references such as Elser [180]. It allows for measuring the response of all combinations of the factors. In this study, the commercially available software Minitab (v.21.2) is used to set up the DOE and to evaluate the results. For flash thermography, the independent variables are the flash energy (kJ) and the sample thickness (mm). The dependent or the calculated variable is the thermal diffusivity (mm^2/s). The value of the thermal diffusivity is calculated using two methods: Parker's half-rise method [12] and the New Least-Squares Fitting method first introduced by Sirikham et al. [181]. Table 3-2 lists the number of runs along with the independent variables for flash thermography. The sample thickness is measured using a digital vernier calliper ten times and then averaged. These averaged values are the ones displayed in the table below. The measurement uncertainty listed in Table 3-2 is taken from the vernier calliper's specified accuracy.

Table 3-2 Full-factorial DOE for flash thermography.

Runs	Flash Energy (kJ)	Sample Thickness (mm)
		(Measurement Uncertainty ± 0.01 mm)
1	2.4	3.86
2	4.8	7.78
3	9.6	5.93
4	9.6	4.87
5	2.4	2.12
6	4.8	4.87
7	9.6	7.78
8	2.4	4.87

9	2.4	5.93
10	4.8	3.86
11	9.6	9.87
12	4.8	3.07
13	2.4	7.78
14	9.6	3.07
15	9.6	3.86
16	4.8	2.12
17	2.4	9.87
18	4.8	9.87
19	4.8	5.93
20	9.6	2.12
21	2.4	3.07

3.3.4 Multi-Parameter Optimisation

As mentioned in Section 4.2, Parker's half-rise equation still remains the most popular method to evaluate material thermal diffusivity. However, since it is only taking the time at which the temperature reaches half the maximum, it is prone to errors, as it does not take into consideration the heat loss at the back wall, which has been highlighted by Chihab [87]. Sirikham et al. introduced the NLSF method to better estimate the thermal wave reflection coefficient [181]. For a given temperature vs. time graph for a sample exposed to flash heating, the method uses the theoretical equation first developed by Lau et al. [182] that describes the temperature behaviour and estimates the unknown parameters using the built-in nonlinear least-square fitting (*lsqnonlin*) solver in MATLAB. While the NLSF algorithm has been used effectively in the reflection mode, its efficiency in determining the thermal diffusivity in the transmission mode has not been investigated. Instead of using just the half-rise time, the entire equation, i.e., Equation (3-5), is used. In the equation, four unknown parameters need to be estimated, which are the thermal diffusivity α , the input energy divided by the product of the material density and specific heat capacity $W = \frac{Q}{\rho C}$, the reflection coefficient R , and the start of sampling time t_s . The addition of the data acquisition time is introduced to allow for using the segment of data that might start after the time $t = 0$, which is the time at which the flash event occurs. This addition is unique and has not been used in previous works such as Krapez et al. [183,184]. It is

worth noting that these models were not applied to PT, specifically in the transmission mode. Additionally, it is important to understand and differentiate the flash energy and sample thickness parameters. To demonstrate the strength of the through-transmission PT technique, only flash energy and sample thickness have been considered, as they are independent variables that have maximum impact on the measurement. The parameters in the multi-parameter optimisation are dependent variables directly from Equation (3-5) that are being estimated resulting from variations in the independent variables. The proposed method finds the optimal parameters based on the following relation:

$$\underset{W,R,\alpha,t_s}{\operatorname{argmin}} \|\tilde{T}(t) - T(t)\| \quad (3-8)$$

Where $\tilde{T}(t)$ is the actual temperature and $T(t)$ is the estimated temperature. The selected initial value for each parameter is as follows: α is the theoretical material thermal diffusivity obtained from the manufacturer, i.e., 14 mm²/s; R is the reflection coefficient, which for the transmission mode would ideally be -1 ; W is determined by the input flash energy (9.6 kJ, 4.8 kJ, and 2.4 kJ); and t_s is 0, assuming the data acquisition started right after the flash event. To ensure that optimisation does not diverge, lower and upper bounds were selected for each parameter. For W , the upper and lower bounds were set 5 times higher and 5 times lower than the initial value. For R , the boundaries were -1.5 and 1.5 . For the thermal diffusivity, the value was set as 10 mm²/s and 20 mm²/s, and the boundaries for t_s were -1 and 1 . Using this function, Equation (3-5) is re-written as follows:

$$T(L, t) = \frac{W}{L} \left[1 + 2 \sum_{n=0}^{\infty} (R)^n \exp \left(-n^2 \pi^2 \frac{\alpha(t + t_s)}{L^2} \right) \right] \quad (3-9)$$

3.4 Results and Discussion

The following subsections present the results obtained in this study. First, the findings from the finite element model are introduced, followed by those from the

laboratory experiments. Finally, a comparative analysis of both approaches is provided.

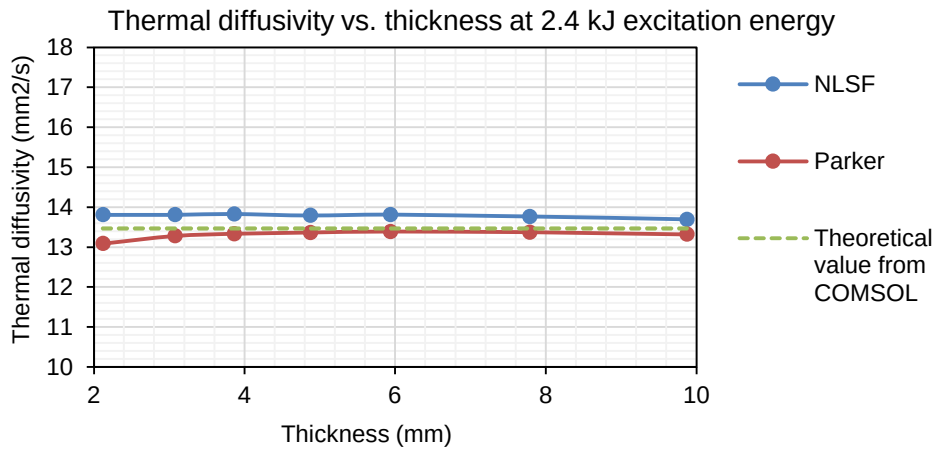
3.4.1 Finite Element Model

Figure 3-4 shows the evaluation of the thermal diffusivity. Based on the thermal material properties listed in Table 3-1 obtained from the material datasheet from the supplier, the theoretical material thermal diffusivity value is $13.47 \text{ mm}^2/\text{s}$. The material thermal diffusivity is estimated using both the NLSF and Parker methods. The NLSF algorithm not only provides an estimate for the thermal diffusivity but also for the input energy Q , the reflection coefficient R , and the starting time of the sampling t_s (the value is 0 for the simulation model as the flash is set to occur at that time). It must be noted that Parker's half-rise method is only able to estimate the thermal diffusivity. From Figure 3-4, it is observed that at all energy levels, the NLSF slightly overshoots the diffusivity value, while Parker undershoots it.

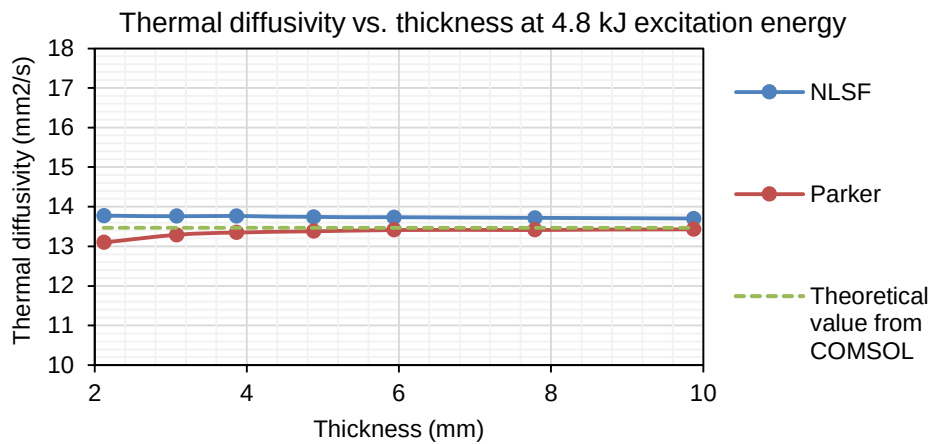
A detailed overview of the NLSF's performance in its four-parameter optimisation is listed in Table 3-3. It shows that the algorithm is most accurate in estimating Q and least accurate in estimating R . Nevertheless, the measurement error is below 5% for all parameters at all energy levels. Furthermore, it is also observed that the percentage error in estimating the thermal diffusivity decreases at 2.4 and 4.8 kJ of input energy. For 9.6 kJ, however, the more accurate estimations are for the thinner plates. Additionally, closely examining the standard deviation for all the estimated parameters reveals that for simulations, the least variation is observed for the input energy of 4.8 kJ.

Figure 3-5 presents the average thermal diffusivity measurements for both methods across all energy levels and sample thicknesses. Observing the measurement error in Figure 3-5, it can be seen that the NLSF offers more accurate estimations for thermal diffusivity at lower thicknesses (thickness $\leq 3 \text{ mm}$), with a percentage error of below 2%. Once the thickness of the sample increases above 3 mm, the estimation error of Parker falls below 1.5%, while that of NLSF remains between 1.5% and 2%. Another observation is that the error in NLSF is found to be more consistent and less susceptible to thickness variations.

Moreover, it should also be highlighted that the NLSF algorithm is estimating four parameters compared to Parker's, which assesses only the thermal diffusivity parameter. NLSF's thickness-independent nature and its ability to estimate multiple parameters demonstrates its superiority to Parker. The advantage of using multi-parameter optimisation is that it accounts for parameters such as input energy (Q), reflection coefficient (R), and sampling time (t_s), which are difficult to measure in practice. These parameters are crucial, as they influence the temperature–time plot of a sample subjected to pulsed heating. Notably, in PT, t_s is assumed to be zero if data capture begins immediately after the flash. However, achieving this would require specialised equipment capable of synchronising the flash with the start of data capture. The use of NLSF algorithms eliminates the need for such equipment as it estimates the time it took after the flash for the data capture to begin.



(a)



(b)

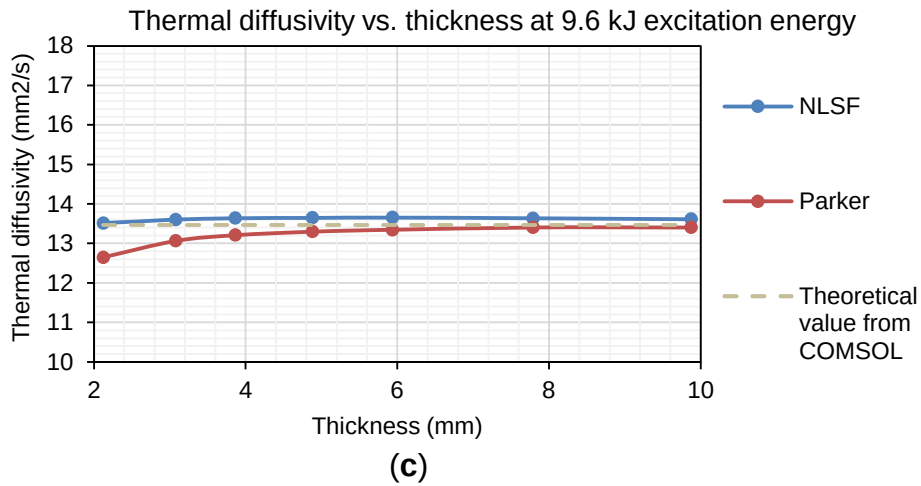


Figure 3-4 Thermal diffusivity measurements using the NLSF algorithm and Parker's method for a 150 × 100 mm S275 steel plate with multiple thicknesses, subjected to different energy levels of pulsed heating simulated in COMSOL. Thermal diffusivity estimates at a) 2.4kJ b) 4.8kJ and c) 9.6kJ

Table 3-3 Error analysis of the NLSF algorithm estimated using the temperature plots obtained from the FEA model in COMSOL with no noise.

Input flash energy 2.4 kJ							
Thickness (mm)	Thermal diffusivity (mm ² /s)	Error (%)	Estimated energy input (kJ)	Error (%)	Reflection coefficient	Error (%)	Sampling time t_s (μs)
2.12	13.81	2.52	2.39	0.42	-1.03	3.00	1.12
3.07	13.81	2.52	2.39	0.42	-1.02	2.00	1.79
3.86	13.83	2.60	2.39	0.42	-1.02	2.00	2.69
4.87	13.79	2.37	2.38	0.83	-1.02	2.00	3.84
5.93	13.81	2.52	2.41	0.42	-1.02	2.00	5.81
7.78	13.77	2.22	2.43	1.25	-1.02	2.00	9.40
9.87	13.70	1.7	2.44	1.67	-1.02	2.00	13.97
Average	13.79	2.35	2.40	0.78	-1.02	2.14	5.52
Standard deviation	0.043	0.31	0.023	0.51	0.0038	0.38	4.67
Input flash energy 4.8 kJ							
Thickness (mm)	Thermal diffusivity (mm ² /s)	Error (%)	Estimated energy input (kJ)	Error (%)	Reflection coefficient	Error (%)	Sampling time t_s (μs)
2.12	13.77	2.22	4.78	0.42	-1.03	2.50	1.00
3.07	13.76	2.22	4.80	0	-1.02	1.90	1.63
3.86	13.77	2.22	4.78	0.42	-1.02	1.70	2.36

4.87	13.74	2.00	4.83	0.01	-1.01	1.00	3.39
5.93	13.73	1.93	4.82	0.42	-1.01	1.00	4.90
7.78	13.72	1.86	4.83	0.01	-1.01	1.00	8.24
9.87	13.70	1.71	4.83	0.01	-1.01	1.00	12.46
Average	13.74	2.02	4.81	0.18	-1.02	1.44	4.85
Standard deviation	0.027	0.20	0.023	0.22	0.0073	0.56	4.14
Input flash energy 9.6 kJ							
Thickness (mm)	Thermal diffusivity (mm ² /s)	Error (%)	Estimated energy input (kJ)	Error (%)	Reflection coefficient	Error (%)	Sampling time t_s (μ s)
2.12	13.52	0.37	9.48	1.25	-1.05	5.00	1.83
3.07	13.60	0.97	9.55	0.52	-1.03	3.00	2.17
3.86	13.64	1.26	9.53	0.73	-1.02	2.00	2.76
4.87	13.65	1.34	9.57	0.31	-1.02	2.00	3.63
5.93	13.66	1.41	9.56	0.42	-1.01	1.10	4.86
7.78	13.64	1.26	9.60	0	-1.01	1.10	7.22
9.87	13.62	1.11	9.62	0.21	-1.01	1.00	10.64
Average	13.62	1.10	9.56	0.49	-1.02	2.17	4.723
Standard deviation	0.048	0.3594	0.046	0.41	0.015	1.44	3.19

To further illustrate the robustness of the NLSF algorithm, several degrees of noise were added to the temperature data obtained from the simulations. The reasons for adding noise to the raw temperature data are several, some of which are mentioned here. Firstly, unlike simulations, temperature data obtained from laboratory experiments have a certain degree of noise embedded within them. The presence of noise can stem from various factors, including

1. Sensor noise, where there is intrinsic noise generated by the IR sensor itself [185].
2. Readout noise generated by reading the signal from the IR sensor [185].
3. Amplifier noise that is added by the amplifiers in the signal processing chain [185].
4. Noise caused by changes in the environmental temperature [186].

5. High humidity levels affecting the readings, as water vapour can absorb and emit IR radiation that can adversely affect the readings [186].
6. Quantisation noise that occurs during the quantisation of the analogue IR signal to digital signal [187].

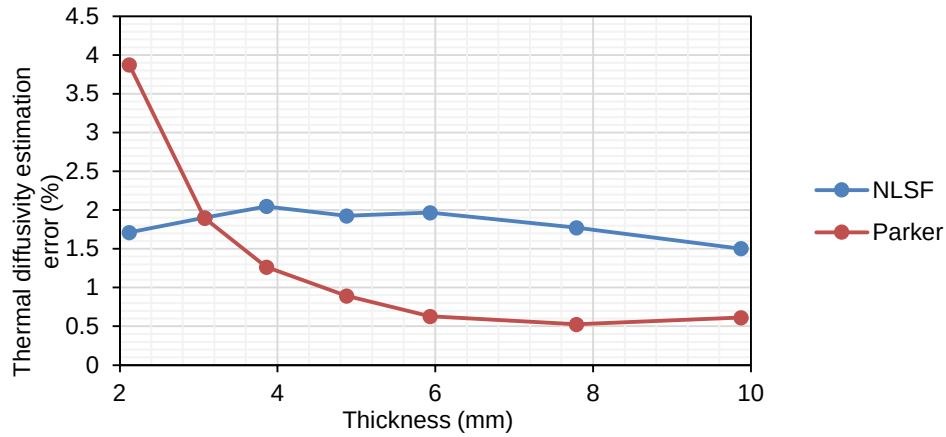


Figure 3-5 Measurement error for NLSF and Parker's method across all thicknesses (values have been averaged across the three different energy levels).

From the list above, points 4 and 5 have been neglected in this study as the technique development is done in a laboratory environment where the humidity levels and temperature are relatively stable and will not produce any significant variation in thermal diffusivity estimation. Moreover, since the sample is matte painted, the environmental effects are also significantly reduced [187].

Secondly, it is important to understand the limitations of the algorithm. The presence of noise can significantly affect the performance of the curve-fitting, and therefore it is necessary to establish the threshold for the algorithm. This will help in identifying the limitations of the algorithm and the conditions under which it is effective. Finally, it serves as a validation technique that will determine whether the algorithm will perform its desired function in practical settings.

Figure 3-6 demonstrates the NLSF algorithm's performance at different SNR levels, ranging from high SNR (40dB) to low SNR (−20dB). The figure shows that even at extremely low SNR levels (e.g., −5 dB), the algorithm is able to predict the thermal diffusivity α (Figure 3-6a) and the input energy level Q (Figure 3-6b)

with the error varying between 0% and 13% for the thermal diffusivity measurement and between 0% and 3% for the energy level measurement. The SNR had to be reduced to -20 dB to get significant variation in the accuracy of the algorithm. While the algorithm estimates four parameters simultaneously, the error analysis in Figure 3-6 has been limited to the thermal diffusivity and energy level measurements. This is because the reflection coefficient R follows a similar pattern to Figure 3-6a,b, and the sampling time t_s has a negligible error (less than 1%) regardless of the noise level. This could be attributed to the fact that the simulation started at $t = 0$ and, regardless of the noise level, the start time is always the same. This shows the robustness of the NLSF algorithm, making it a practical alternative for measuring the thermal diffusivity of materials as well as estimating multiple parameters for a pulsed thermographic inspection. Since the error levels for SNR levels -5dB to 40dB in Figure 3-6b are extremely low a zoomed in figure is provided for clarity. The justification for choosing NLSF over Parker is further strengthened by Figure 3-7, where a comparative analysis of both methods' accuracy in estimating thermal diffusivity at varying SNRs is presented. Our research demonstrates that Parker delivers more accurate measurements at a higher SNR. A critical analysis reveals that the technique offers larger variation from the mean value when compared to the NLSF algorithm. Further, the analysis also confirms that at a lower SNR (-20 dB), the NLSF exhibits a much lower error ($\approx 60\%$) compared to Parker ($\approx 1600\%$), as shown in Figure 3-7. It can be inferred from Figure 3-7 that the percentage errors decrease significantly when the SNR is 10 dB or higher. To provide a more detailed view of these errors, the insets within the red boxes offer a magnified view of each plot. These zoomed sections reveal that, as SNR increases, the Parker method tends to yield more accurate measurements of thermal diffusivity. Nonetheless, the NLSF algorithm also delivers comparable results across the range of SNRs. Additionally, the NLSF algorithm offers estimates for multiple parameters, including the input energy Q , reflection coefficient R , and sampling start time t_s , in addition to thermal diffusivity. This comprehensive capability makes it a more versatile and appealing option for thermal diffusivity estimation.

Finally, one of the main reasons for conducting a full-factorial DOE is to identify the parameter that has the most sensitivity toward the thermal diffusivity measurement. The answer to this question was achieved by using the “Analyse Factorial Design” option in Minitab. The Pareto charts in Figure 3-8 show the effect that the input variables, i.e., the sample thickness and flash energy level, have on estimating the material thermal diffusivity. The variables are on the y-axis, and their corresponding standardised effects are on the x-axis. Standardised effects simply mean that the effects of the parameters are scaled based on their standard error, which allows us to compare the significance of the two factors. The vertical red dashed line at 2.179 represents the point where the significance level is 0.05. If the standardised effect of a factor exceeds that line, then it means that the factor is considered to be statistically significant. Figure 3-8a shows the effect of the thickness and energy level in estimating thermal diffusivity using the NLSF algorithm where it can be seen that the flash energy plays a significant role in influencing the outcome of the thermal diffusivity measurement. In contrast, the role of sample thickness is shown to be not statistically significant in this particular case, and, therefore, it did not play a major role in influencing thermal diffusivity measurement. Given that thermal diffusivity is supposed to be an intrinsic material property, the result is in line with what was expected. However, the outcomes are flipped in Figure 3-8b, where the sample thickness is shown to play a much more significant role in estimating material thermal diffusivity compared to the flash energy level when the measurement method is Parker’s half-rise equation (Equation (3-7)). It is also important to note that, in this case, both factors exceed the threshold for a standardised effect (indicated by the red vertical line at 2.179), demonstrating their significant influence on thermal diffusivity estimation. However, the effect of flash energy is smaller relative to that of thickness. This means that variations in thickness introduce greater variability into the thermal diffusivity estimates using Parker.

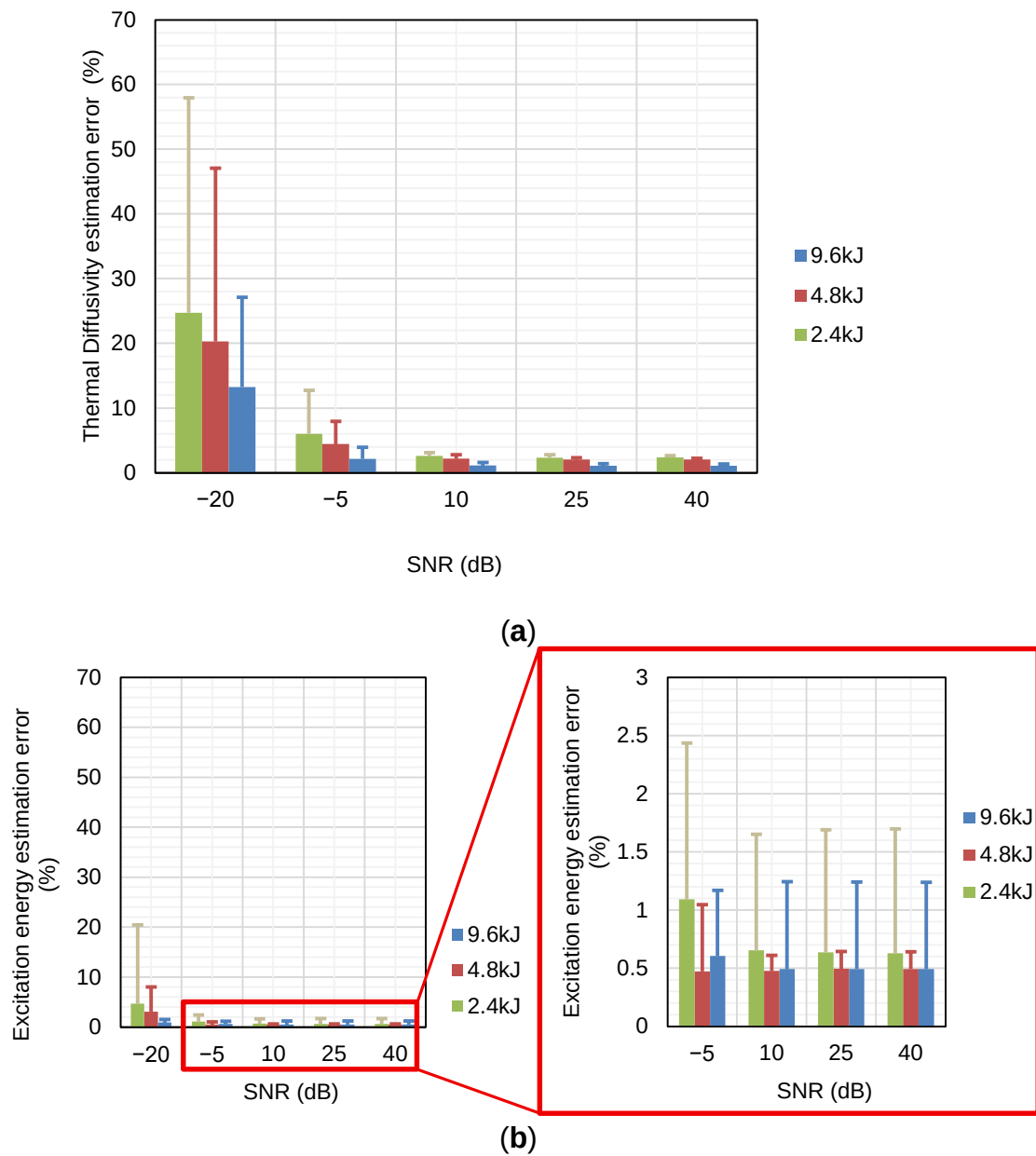
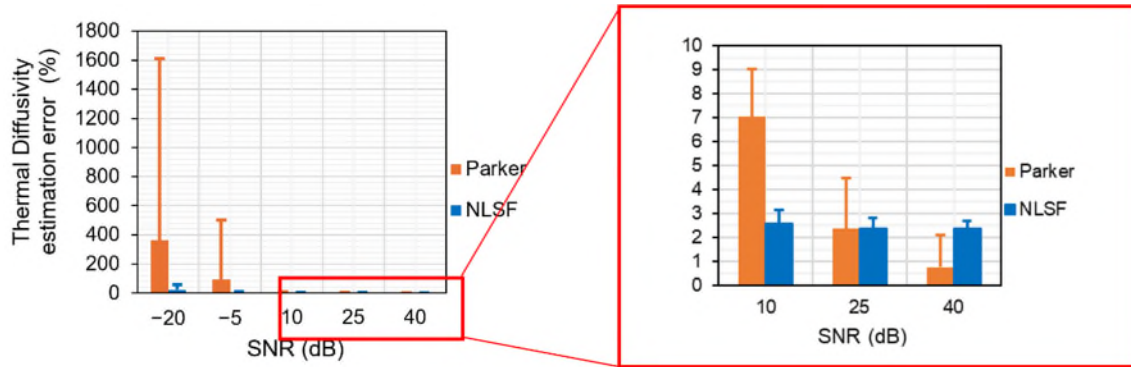
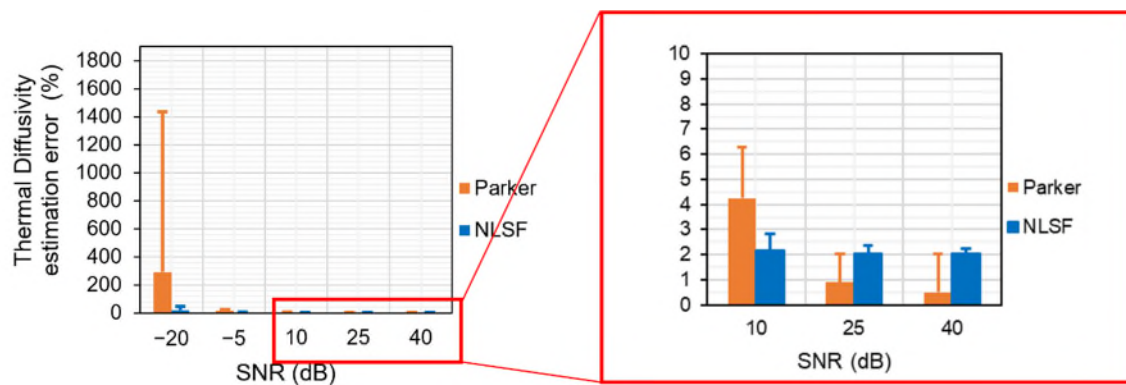


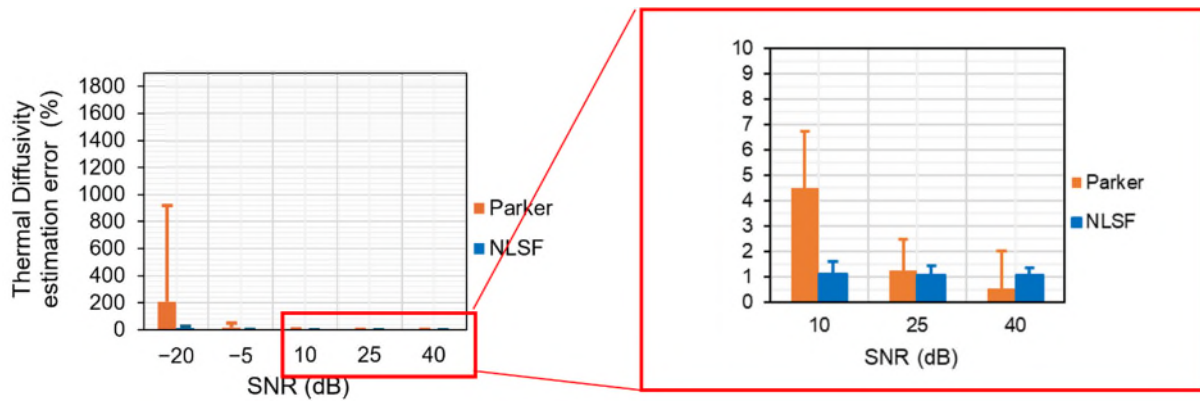
Figure 3-6 Error analysis of the NLSF algorithm with varying SNRS for (a) thermal diffusivity measurement and (b) input energy measurement using the temperature plots obtained from the FEA model in COMSOL.



(a)



(b)



(c)

Figure 3-7 Comparison of Parker's and NLSF method's performance at estimating thermal diffusivity at different SNRs for energy levels (a) 2.4 kJ, (b) 4.8 kJ, and (c) 9.6 kJ.

Combining the observations in Table 3-3 and Figure 3-8, it can be said that the NLSF algorithm would be the preferred method of choice as it is not sensitive to sample thickness, and a high energy level such as 9.6 kJ should be used to ensure that the error in thermal diffusivity measurement is minimised. Higher energy leads to a greater temperature change at the back wall, improving the SNR. This will lead to more accurate measurements of thermal diffusivity. The noise equivalent temperature difference (NETD) of the IR sensor dictates the extent of signal variation observed when the camera captures electromagnetic radiation from a temperature-stabilized flat-field target [188]. From a practical perspective, this aligns with the established understanding of an IR sensor's sensitivity to temperature variations. Any temperature variation below this NETD is undetectable by the camera. Consequently, the detection threshold for an IR sensor, ΔT , as described by Shepard et al. [188], is defined as $\Delta T = n\sigma$, where σ represents the NETD and n is a multiplication factor to ensure that ΔT is at least n times greater than the NETD. While a case could be made that Parker's half-rise equation delivers more accurate results at higher thicknesses, as illustrated in Figure 3-5, the difference in the error values is not significant enough to write off the ability of the NLSF algorithm to estimate thermal diffusivity at higher thickness, as both methods deliver a negligible uncertainty level for practical applications.

The purpose of the residual plots in Figure 3-9 is to validate the assumptions for the regression model for thermal diffusivity measurements for both the NLSF (Figure 3-9a) and Parker (Figure 3-9b) methods. The term "residual" itself simply refers to the difference between the observed value and the value predicted by the model. For both approaches, the figure in the top left is the "normal probability plot", which shows that the residuals are approximately normally distributed. The plot on the top right is the "residuals vs. fits" plot that indicates no obvious patterns, which suggests that the linearity and homoscedasticity assumptions are met. This means that the variance of the residuals is constant across all levels of fitted values. The histogram in the bottom left plot reiterates the normality assumption, as the results roughly display a symmetric distribution. The "residual vs. observation order" plot, displayed in the bottom right of Figure 3-9 shows that

residual values are scattered randomly without any discernible patterns, as they are plotted against the order of data collection. This random distribution suggests that there is no autocorrelation present, affirming that the values are independent of one another. Such independence is crucial, because it validates the assumption in the regression analysis that the errors in the data collection and prediction processes do not influence each other, thereby supporting the reliability and accuracy of our model's findings. Finally, it is observed that residual values are similar for both the NLSF algorithm and Parker's half-rise method, indicating that the choice of method has negligible effect on the thermal diffusivity measurement.

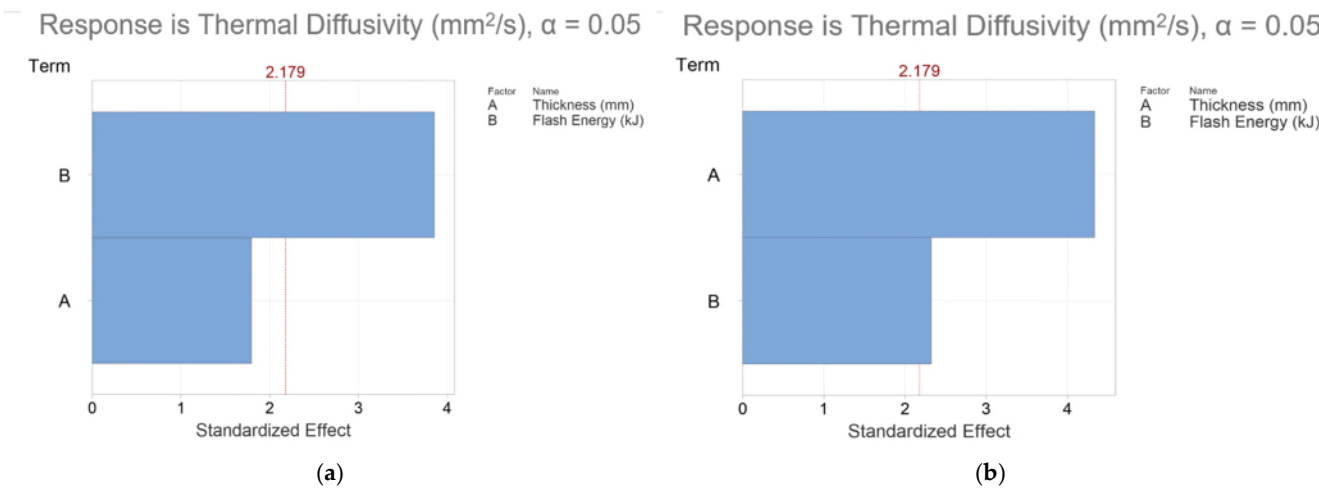
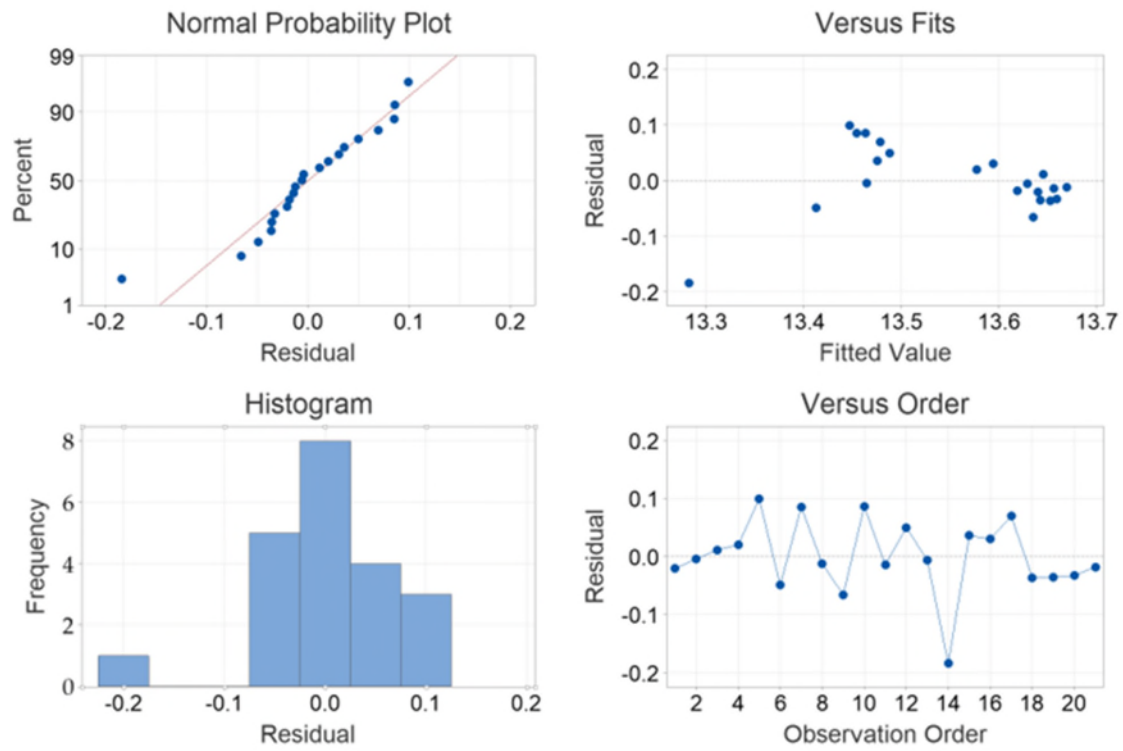
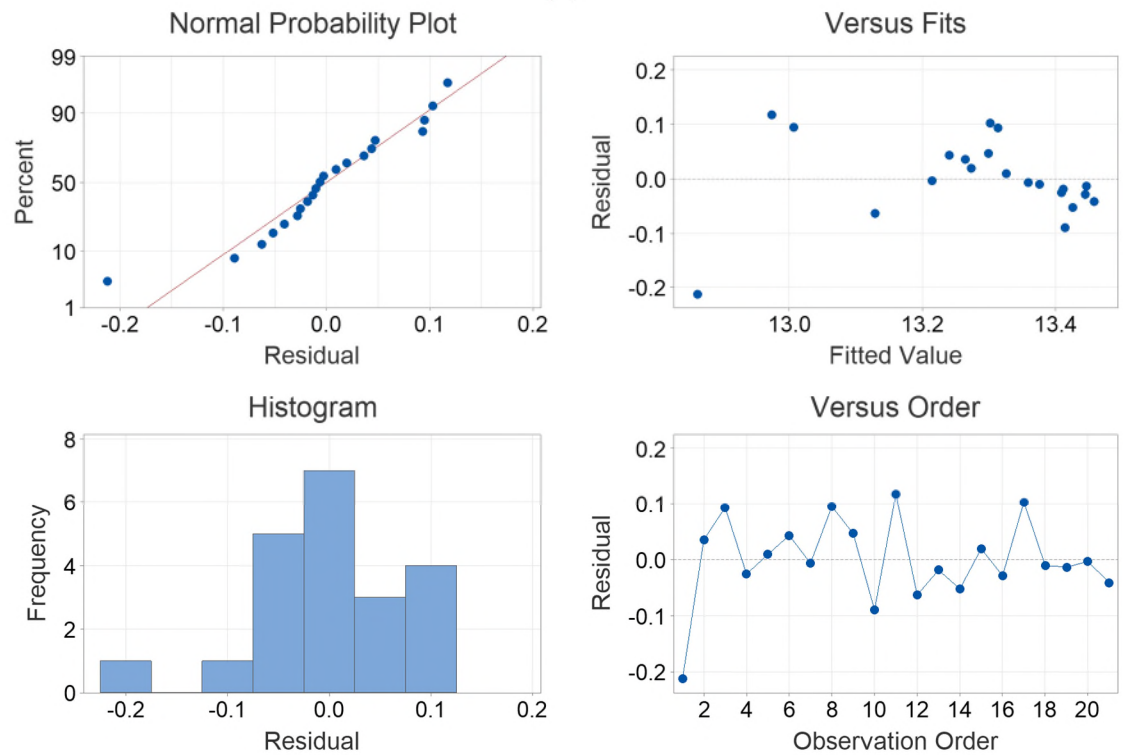


Figure 3-8 Pareto charts for standardised effects for the finite element simulations (a) thermal diffusivity estimated using NLSF and (b) thermal diffusivity estimated using Parker's method.



(a)



(b)

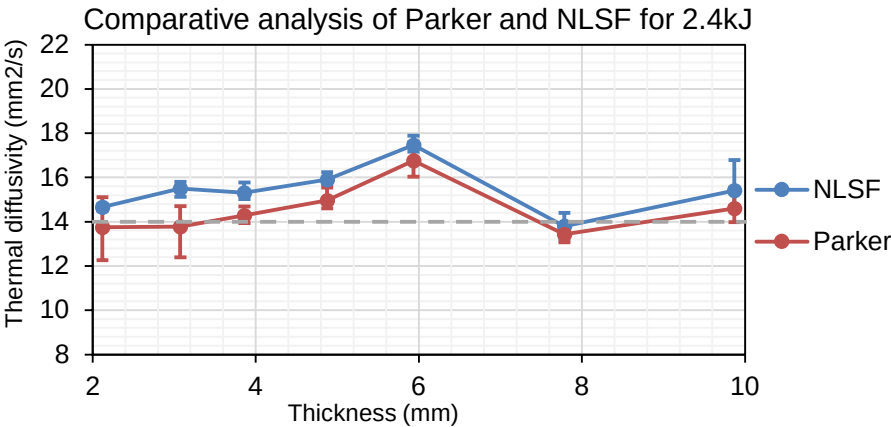
Figure 3-9 Residual plots from the finite element simulations for estimating thermal diffusivity using (a) NLSF and (b) Parker's method.

3.4.2 Results from Laboratory Experiments

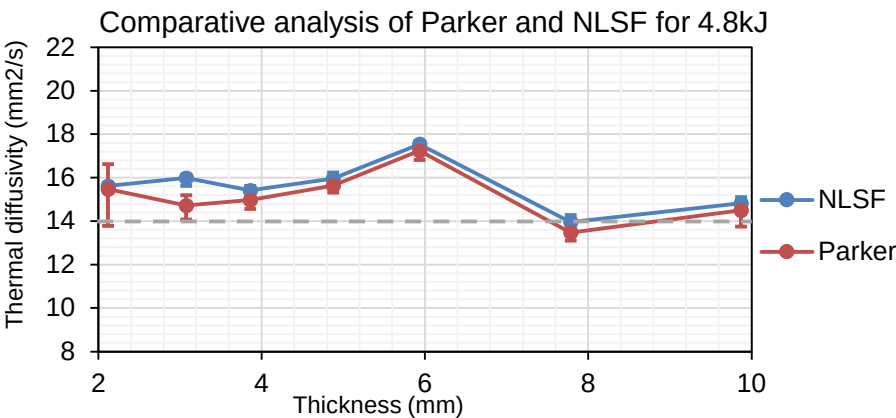
As mentioned in the previous section, the temperature rise at the back wall can be prone to heat losses that might negatively affect thermal diffusivity calculations. Furthermore, the sensitivity of thermal diffusivity to IR camera standoff distance from the sample is also subject to investigation. To address these challenges, a random sample (3.859 mm thickness) was chosen from the selection of samples and was subjected to flash heat of 9.6 kJ. The back wall temperature information was collected at three different standoff distances: 200 mm, 250 mm, and 300 mm. The justification for using these distances was to cover an entire range of distances that were deemed practical for data capture. At distances below 200 mm, the entire sample was not fully captured within the camera's field of view, while at distances beyond 300 mm, the sample occupied a minimal portion of the frame. To reduce random noise generated by the IR signal, a total of 10 repeats were conducted and averaged. For each run, the temperature measurements were recorded at the back wall for a total of 10 s with a region of interest (ROI) set to a 100×100 pixel square at the centre of the sample to negate thermal losses that might result from edge effects, which negatively affect the results [177,178] (at a standoff distance of 300 mm, each pixel corresponds to approximately 0.4 mm). This was done to ensure that temperature saturation, i.e., the maximum temperature that the back wall can reach, was within the captured range. To ensure that the captured dataset was indeed repeatable, the p -value estimate obtained via an analysis of variance (ANOVA) was determined using the built-in "data analysis" tool available in Microsoft Excel. If the p -value is less than $\alpha = 0.05$, then there is a significant deviation between the results. For comparison, if each of the repeats had the exact same value, the p -value would be 1. When all the 10 s of data were considered for the repeats, the p -value was significantly less than 0.05. To determine the appropriate data segment, two conditions were set that needed to be satisfied in order to achieve a more accurate measurement. First, temperature saturation must have occurred at the back wall, and second, the p -value should be close to or above 0.9. Thermal diffusivity was then estimated by averaging the results of the 10 runs. For this assessment, the NLSF algorithm was used to

determine the thermal diffusivity. The analysis revealed that, regardless of the standoff distance used, the estimated thermal diffusivity was the same up to two decimal points. This practice of conducting 10 repeats was then repeated for all the runs in the experiments.

Similar to the FEM analysis, it was important to compare the thermal diffusivity measurement using both Parker's half-rise equation and the NLSF algorithm. Figure 3-10 shows the thermal diffusivity measurements using both methods at different energy levels. Similar to what is observed in Figure 3-4, Parker's half-rise method seems to provide a slightly lower estimate for the thermal diffusivity at all thickness values and energy levels. Nonetheless, both methods follow a similar pattern for thicknesses above 4mm.



(a)



(b)

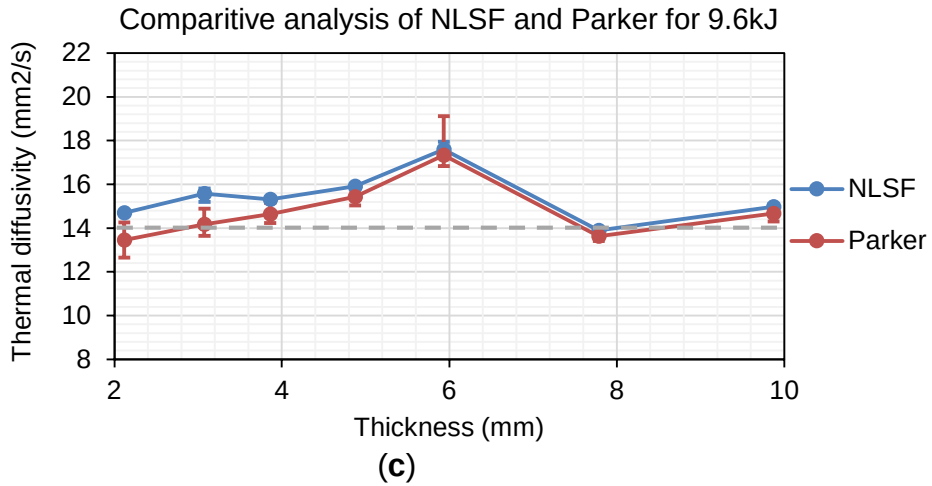


Figure 3-10 Thermal diffusivity estimations for different thicknesses at a) 2.4kJ, b) 4.8kJ, and c) 9.6kJ using NLSF and Parker's methods. (grey dashed lines represent the thermal diffusivity value provided by the supplier)

In terms of variation between the two methods based on the plots, it can be observed that at 4.8 kJ, the estimated values are closest to each other, indicating that this energy level may be optimum for thermal diffusivity measurement. The largest variation is observed within the plots obtained at 2.4 kJ of energy. The cause for this variation will be discussed in a later section. Based on the plots, several observations can be made. Firstly, the closeness of the estimated values using both methods across energy levels indicates the reliability of the estimated values. This result is consistent with expectations, as the NLSF algorithm continues to utilize the equation formulated by Parker. It is just not assuming the half-rise assumption that Parker developed on top of his equation for the temperature rise at the back wall. Secondly, the closeness in the measurement values also suggests that the methodology is robust, and therefore, the results were obtained following the same procedure that was outlined in the discussion section regarding the camera standoff distance. Thirdly, the estimated values are indicative of the true material thermal diffusivity. Compared to the value of 14 mm²/s provided by the supplier, the estimated values do cluster around this value. The only major anomaly in the results is the thermal diffusivity measurement for the sample at 5.93 mm, which was much higher (≈ 18 mm²/s). This high value for thermal diffusivity compared to the rest of the samples was observed in all the 10 repeats conducted for this sample. This anomaly is seen using both Parker and

NLSF at all energy levels, so this does not reduce the reliability of the methodology; however, it is something that requires further investigation. Excluding this result, the maximum percentage difference from the supplier value is 13.27% obtained for the sample with thicknesses of 3.07 mm at 4.8 kJ flash energy. Finally, the plots show repeatability, as both methods estimate similar values for thermal diffusivity across different energy levels.

Figure 3-11a,b isolates the measurement methods and show the variation of thermal diffusivity measurements at the three different energy levels. The estimated values show a greater level of consistency at higher thickness values. For the NLSF method, the diffusivities estimated at 9.6 kJ and 4.8 kJ are in close agreement with a slightly higher variation at 2.4 kJ, where a higher value is estimated, especially for the 9.87 mm thick sample. This variation is not visible with Parker's half-rise method, which is in line with the simulation results that indicate a greater level of accuracy in thermal diffusivity measurements at higher thicknesses. Overall, the NLSF method provides a higher level of repeatability, especially at higher energy levels, and both methods exhibit a similar trend for thermal diffusivity measurement.

The histograms in Figure 3-12 display the variation of thermal diffusivity using both methods at different energy levels. Both methods provide a bell distribution with the median value for all the runs to be between 15 mm²/s and 16 mm²/s. A closer review of the data, however, reveals that the range of thermal diffusivity values estimated using Parker at 4.8 kJ and 9.6 kJ is slightly larger (13–17 mm²/s) compared to NLSF (14–17 mm²/s). At 2.4 kJ, both methods offer the same level of variability in thermal diffusivity estimation. For NLSF, it is observed that the energy level has a negligible effect on the overall variability in thermal diffusivity estimation. A detailed analysis of the thermal diffusivity measurement is provided in Table 3-4. The term "CV" refers to the coefficient of variation, which is the mean divided by the standard deviation. This term measures the dispersion of data points in a data series around the mean.

The bottom row for each estimation method (NLSF and Parker's) represents the overall mean of the thermal diffusivity values and their corresponding coefficient

of variation (CV) from the rows above. Overall, the obtained CV using NLSF is much lower than the one obtained using Parker’s method, indicating that the precision of the NLSF is higher. For each individual thickness, the CV is lower at higher energy levels.

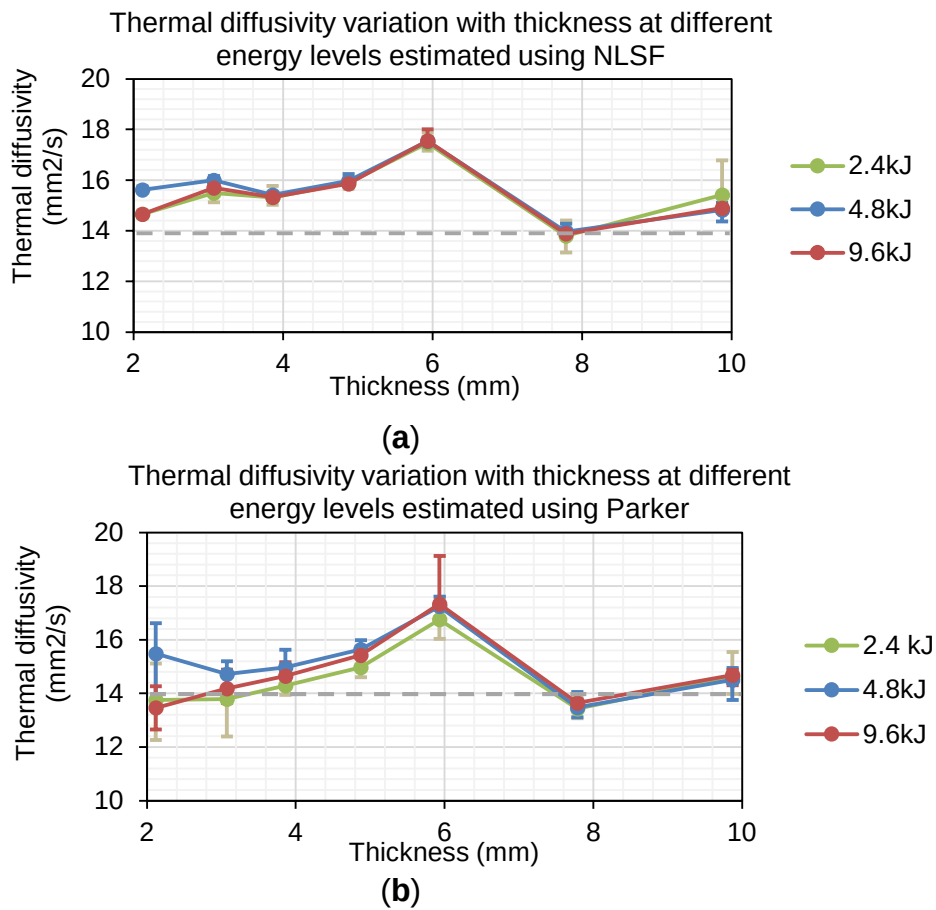
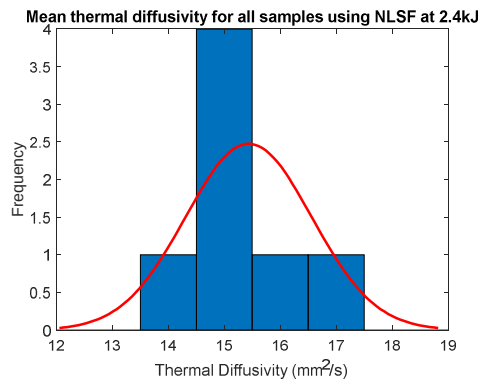
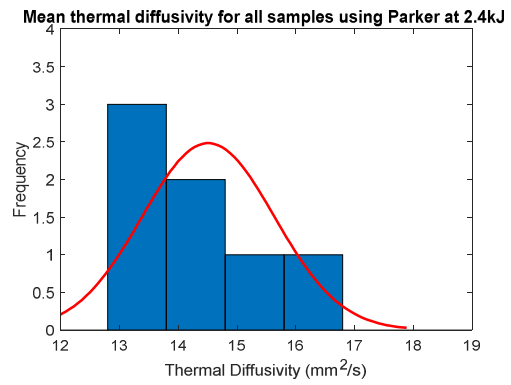


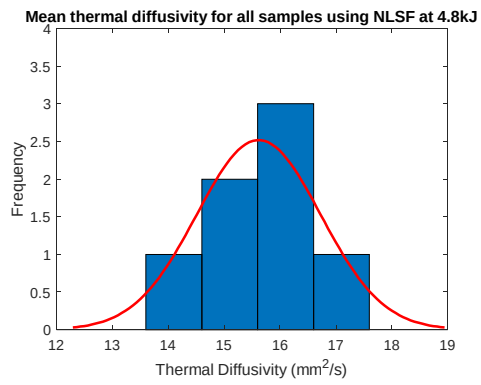
Figure 3-11 Thermal diffusivity measurements for varying thicknesses at different energy levels, estimated using (a) NLSF and (b) Parker’s method.



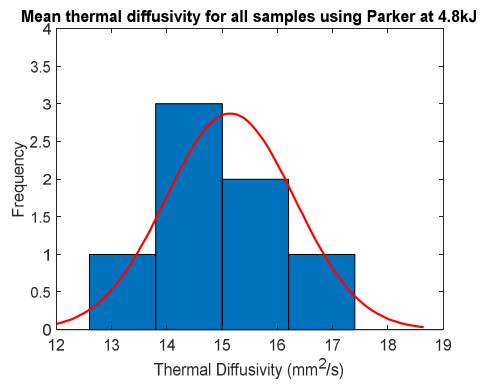
(a)



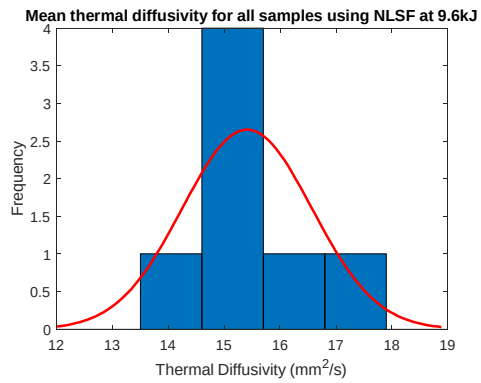
(b)



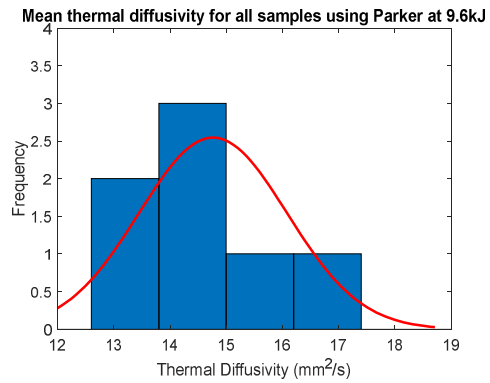
(c)



(d)



(e)



(f)

Figure 3-12 Histograms showcasing variations in thermal diffusivity with different thicknesses at different energy levels estimated using NLSF (a,c,e) and Parker's methods (b,d,f).

Table 3-4 Mean thermal diffusivities for different thicknesses at different energy levels and their corresponding coefficient of variations estimated using NLSF and Parker's methods.

NLSF						
Thickness (mm)	Mean diffusivity at 2.4 kJ (mm ² /s)	CV (%)	Mean diffusivity at 4.8 kJ (mm ² /s)	CV (%)	Mean diffusivity at 9.6 kJ (mm ² /s)	CV (%)
2.12	14.66	0.67	15.62	0.40183	14.66	0.35052
3.07	15.49	1.49	15.99	1.16981	15.69	1.08882
3.86	15.31	1.14	15.42	0.33212	15.33	0.39875
4.87	15.90	1.10	15.97	0.75168	15.86	0.27864
5.93	17.47	1.22	17.54	0.60735	17.55	0.96350
7.78	13.80	2.46	13.97	1.07911	13.88	0.58508
9.87	15.42	4.28	14.82	1.64175	14.90	0.54605
Overall mean	15.43	6.8	15.62	6.53	15.41	6.94
Parker						
Thickness (mm)	Mean diffusivity at 2.4 kJ (mm ² /s)	CV (%)	Mean diffusivity at 4.8 kJ mm ² /s)	CV (%)	Mean diffusivity at 9.6 kJ mm ² /s)	CV (%)
2.12	13.75	7.03	15.48	6.75	13.46	4.69
3.07	13.78	4.46	14.72	2.69	14.18	3.31
3.86	14.28	2.07	14.97	2.43	14.65	2.00
4.87	14.97	1.99	15.63	1.31	15.43	1.67
5.93	16.76	3.16	17.25	1.62	17.33	3.75
7.78	13.43	1.86	13.48	2.13	13.64	0.76
9.87	14.60	3.96	14.50	2.50	14.68	1.03
Overall mean	14.51	7.17	15.15	7.13	14.77	8.26

A plausible explanation, as explained earlier, is that higher energy levels cause a greater temperature rise at the back wall. This means that the noise generated from the IR radiometer has less influence on the thermal diffusivity measurement. At lower energy levels, the back wall temperature will be lower. This means that the SNR is lower, which in turn causes a larger variation in the temporal plots of consecutive runs. In terms of the difference in the total mean at different energy levels, the means obtained using NLSF exhibit a greater degree of closeness compared to Parker's method, once again building a stronger case for the use of NLSF for thermal diffusivity measurement as it offers greater repeatability. For the CV values, again, the NLSF displays a lower variation compared to Parker's method. An additional consideration that must be taken here is that the CV values are higher due to the inclusion of the thermal diffusivity obtained from the sample that has a thickness of 5.93 mm. Removing this value will significantly reduce the

CV for both methods at all energy levels. For this reason, the rest of the results have excluded these values. Figure 3-13 shows the Pareto charts for both the NLSF and Parker methods. For the NLSF, the influence of energy levels is insignificant, as seen in Figure 3-13a, and the effect of material thickness seems to dominate the thermal diffusivity measurement. This outcome is logically consistent, as the thermal diffusivity measurements exhibited greater variability with changes in thickness compared to the simulations. However, the change does not exhibit any identifiable pattern, i.e., it is random. The fluctuation of the thermal diffusivity with thicknesses can possibly be reduced by extending the full-factorial DOE by adding repeats of multiple samples with the same material and thickness. For Parker's method, while both factors display statistical significance in measurement, the thickness seems to have a greater influence on the measurement than the energy level. A final comparison of the coefficient of variation is done in Figure 3-14, excluding the estimated values for the 5.93 mm-thick sample. Figure 3-14a shows the mean CV at different thicknesses averaged for all energy levels. Overall, NLSF offers a much lower CV, although the values are similar for both methods at higher energy levels. It is also observed that Parker's method is more susceptible to inaccuracies at lower thickness levels, similar to what was observed in the FEM results. Once again, similar to Figure 3-11, the measurement methods are isolated to observe the effect of the energy levels at different thicknesses. It can be observed that at 9.6 kJ and 4.8 kJ, the SNR from the NLSF algorithm (Figure 3-14b) is sufficiently high to maintain a CV value of less than 2%, even at the highest thickness values, i.e., 9.87 mm.

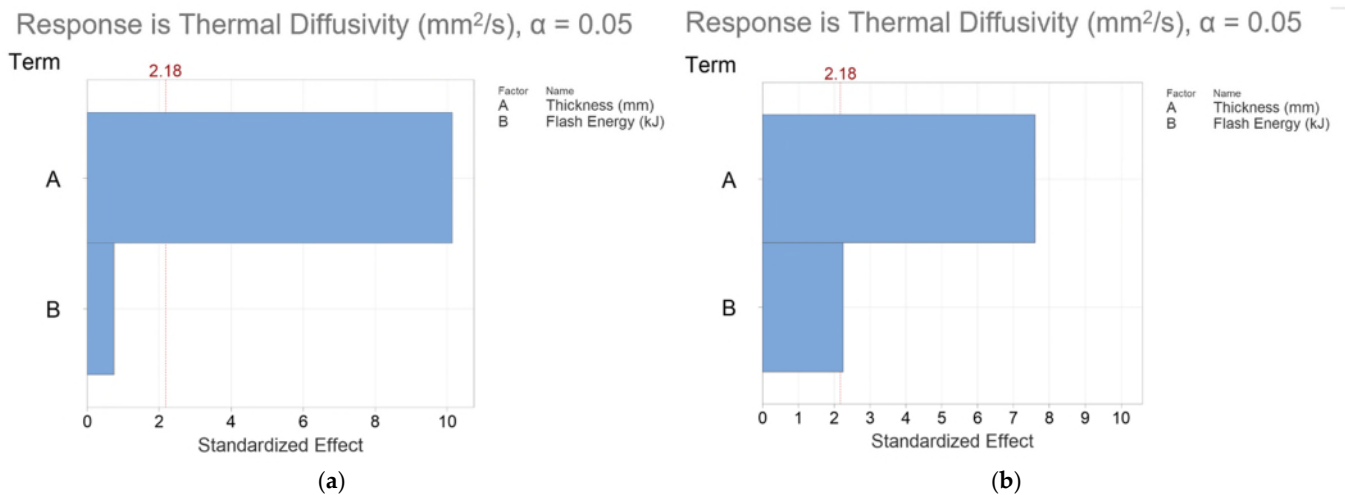
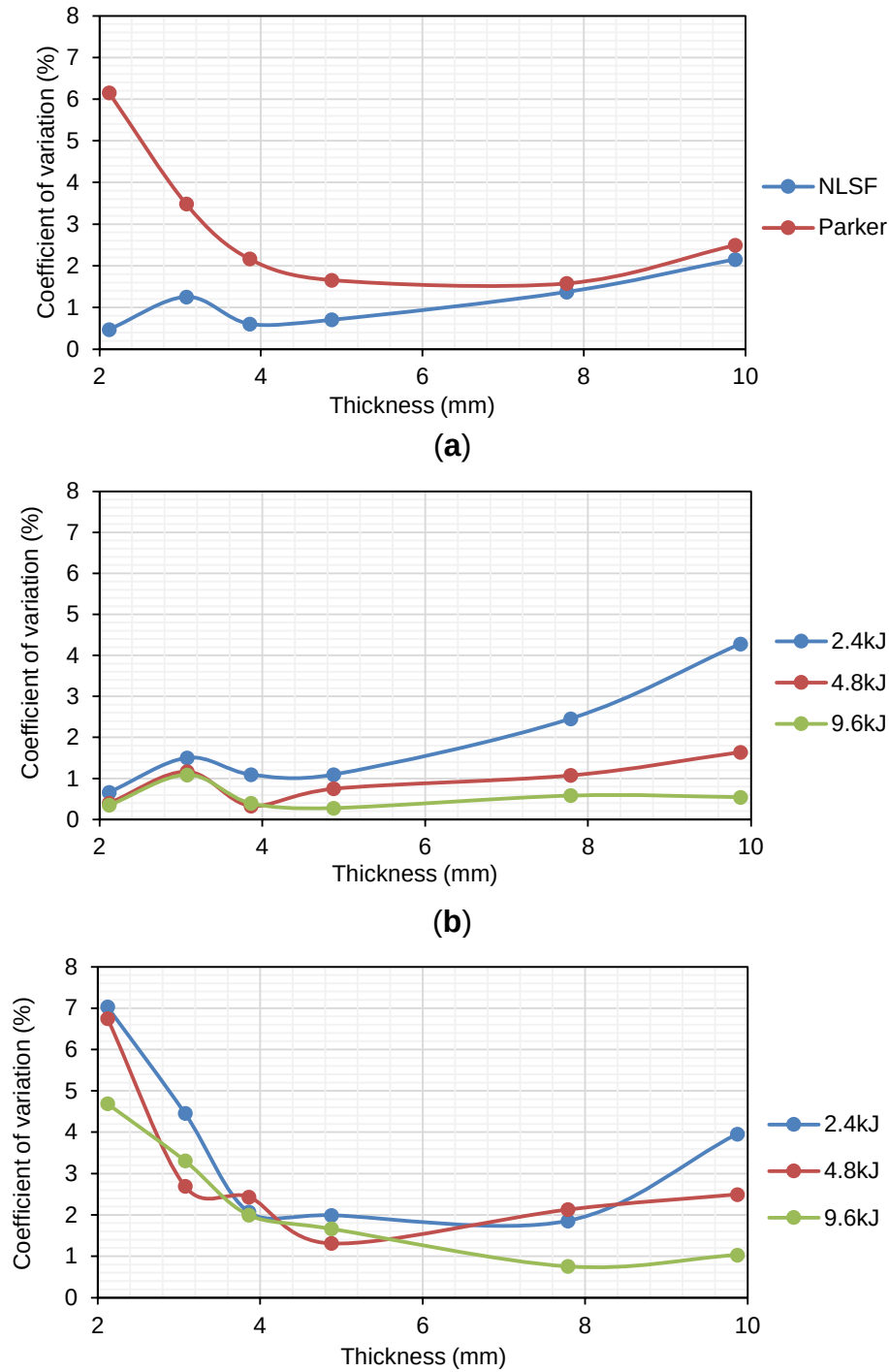


Figure 3-13 Pareto charts for standardised effects for the laboratory experiments
(a) thermal diffusivity estimated using NLSF and (b) thermal diffusivity estimated
using Parker’s method.



(c)

Figure 3-14 Comparison of the coefficient of variation (a) comparison between the NLSF and Parker methods, (b) variation at different thicknesses using the NLSF method, and (c) variation at different thicknesses using Parker's method.

The increased CV value at higher sample thicknesses and lower energy values can be attributed to the fact that this particular setting does not cause the back wall temperature to rise significantly. Combining the lower energy level with a higher sample thickness results in the back wall temperature signal being significantly corrupted by noise. Higher noise levels result in greater variability in thermal diffusivity estimates. For Parker's method, the CV values are higher, especially at the upper and lower bounds of the thickness range. Unlike the NLSF method, a clear pattern cannot be observed, and the CV values are more randomly spread. Nevertheless, it can be concluded that Parker's method yields more precise thermal diffusivity estimates for data captured at higher energy levels and for higher thickness values. A comparison between Figure 3-14a,b shows that the NLSF algorithm outperforms Parker, as it achieves a lower overall CV across all thicknesses and energy levels when estimating thermal diffusivity.

3.4.3 Comparison Between FEM and Laboratory Experiments

One of the research gaps highlighted by Ali et al. [14] was the limited number of FEA models that describe the back-wall temporal behaviour of a sample subjected to pulsed heating. One of the reasons for this could be the fact that the current models are not a true representative of real-life conditions since there are other factors that may cause disparities between simulation and laboratory experiments. Moreover, current FEA models have focused mainly on the reflection mode and the identification of defects, as shown by Kalyanavalli et al. [106]. The current literature does not contain many FEA models that describe temporal behaviour using the transmission mode. Furthermore, comparisons of the thermal diffusivity measurements using FEA and laboratory experiments are also extremely limited [106,189]. This research attempts to understand the disparity between FEA and laboratory experiments. For this purpose, Figure 3-15 was generated, which compares the thermal diffusivity measurement using both

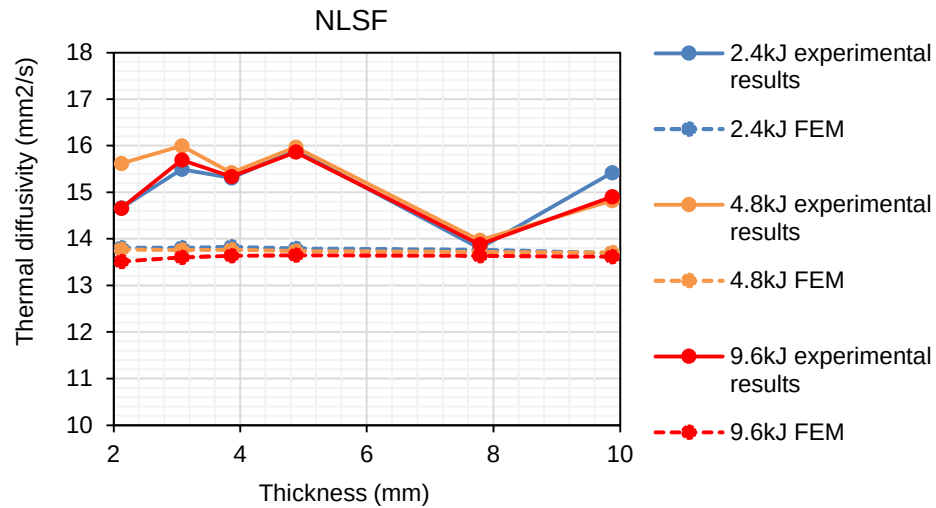
NLSF and Parker's methods. For the comparison, the thermal diffusivity for all samples, excluding the 5.93 mm thick sample, was considered. For the laboratory experiments, a total of 10 repeats were conducted for each thickness, with the displayed points representing the average of those runs. In contrast, repeats were not performed for the simulations, as the consistent nature of the simulation environment ensures identical results for the same input parameters.

Figure 3-15a,b shows that the results are far more consistent in the simulations compared to the laboratory experiments. Furthermore, there seems to be a systematic shift in the measurement for the laboratory experiments. This shift highlights several factors that have not been discussed in existing research within this context. These are:

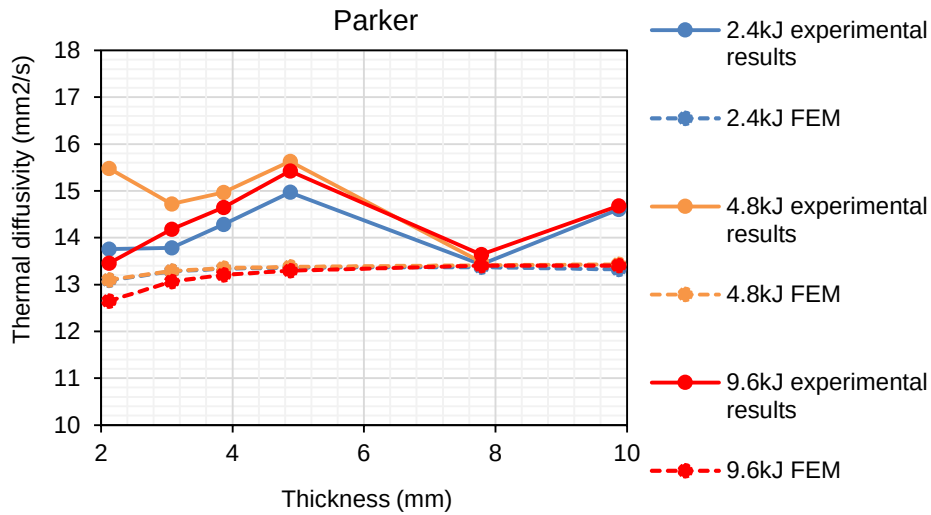
- Planck's law of blackbody radiation shows that there is an inverse relationship between the wavelength and the peak emission of electromagnetic radiation. This factor is not present in the simulation model as it applies pulse energy, assuming that it uniformly causes a temperature rise on the surface of the sample. This means that the energy distribution across wavelengths is assumed to be equal across different energy levels in the simulation model. In the laboratory experiments, as the energy of the flash reduces, the peak emission shifts to a longer wavelength. In our case, the IR radiometer has a fixed wavelength range (3–5 μm), so the captured radiation does not truly represent the spectral radiance of the body.
- As mentioned in the previous subsection, the SNR at lower energy levels is lower. This means that the noise levels are more prominent since the temperature increase at the back wall is much lower. While, theoretically, a low temperature increase should not affect the thermal diffusivity measurement as seen in the simulations, it does in laboratory experiments. This is because the temperature measurement systems, especially the IR radiometers' (NETD), are a limiting factor. This factor determines the smallest temperature

difference an IR radiometer can detect. At lower energy levels, the low temperature increase at the back wall can adversely affect the camera's ability to capture accurate and meaningful thermal data. Nevertheless, based on Figure 3-15a, it can be observed that even at lower energy levels, i.e., 2.4 kJ, the NLSF algorithm still manages to provide thermal estimates that are closer to each other compared to Parker, further strengthening its thermal diffusivity estimation capabilities.

- Deviations can occur within the material composition itself. FEA models assume that the entire structure is homogeneous, which will result in repeatable results for intrinsic material properties such as thermal diffusivity. This is not the case for laboratory experiments, as demonstrated by our results, which showed variations in thermal diffusivity for the same material composition.
- Uncertainties may arise from repeated tests. In simulations, regardless of the number of repeats done, if input parameters are the same, the output (in this case, the temperature plots at the back wall) will be the same. However, in experimental conditions, it is nearly impossible to achieve such a result; hence, there is a disparity between runs, even for the same sample. The effect of the last two parameters has been documented previously in [173].
- Deviations can occur based on the heating pattern. For the simulations, a heat flux distributed uniformly across the sample is applied. However, for the laboratory experiments, two flash lamps are used to thermally excite the specimen. Unlike simulations, the heat distribution across the sample surface in laboratory experiments is uneven, which can negatively affect the accuracy of thermal diffusivity measurements. Moreover, while the energy level at the source of the flash lamps might be a certain value, the nominal value that is deposited at the surface would be significantly less, as demonstrated by Krankenhagen et al. [190].



(a)



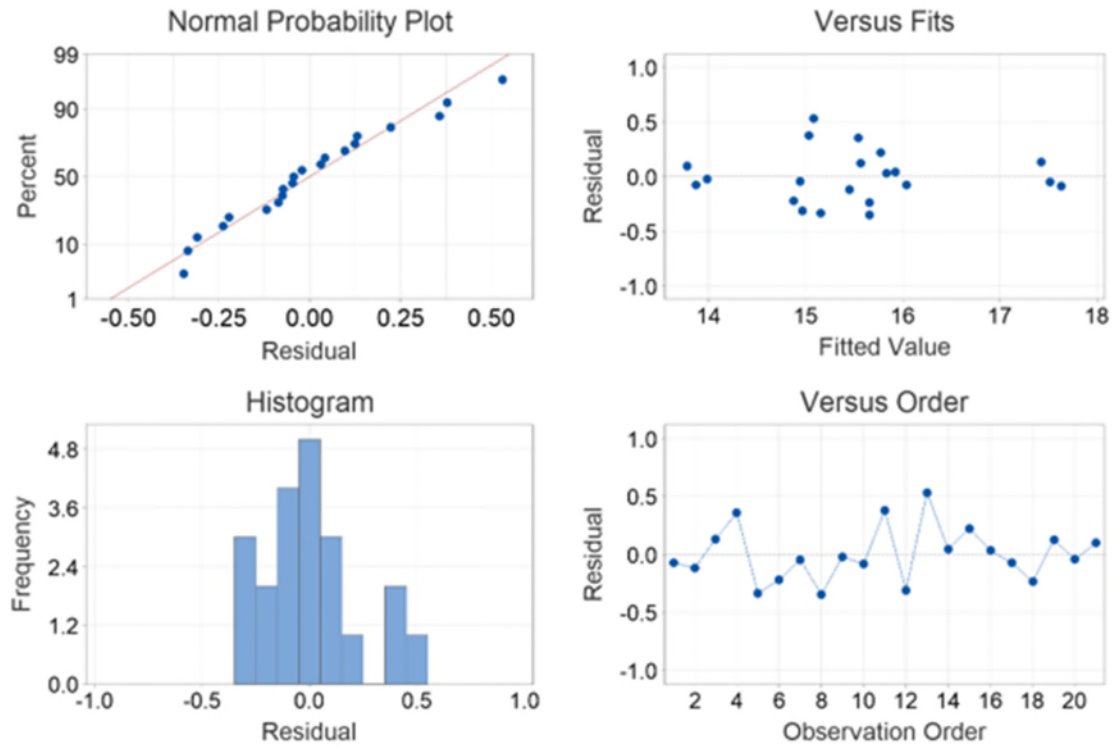
(b)

Figure 3-15 Comparison between simulation and laboratory experiments for thermal diffusivity measurement (a) using the NLSF method and (b) using Parker's method.

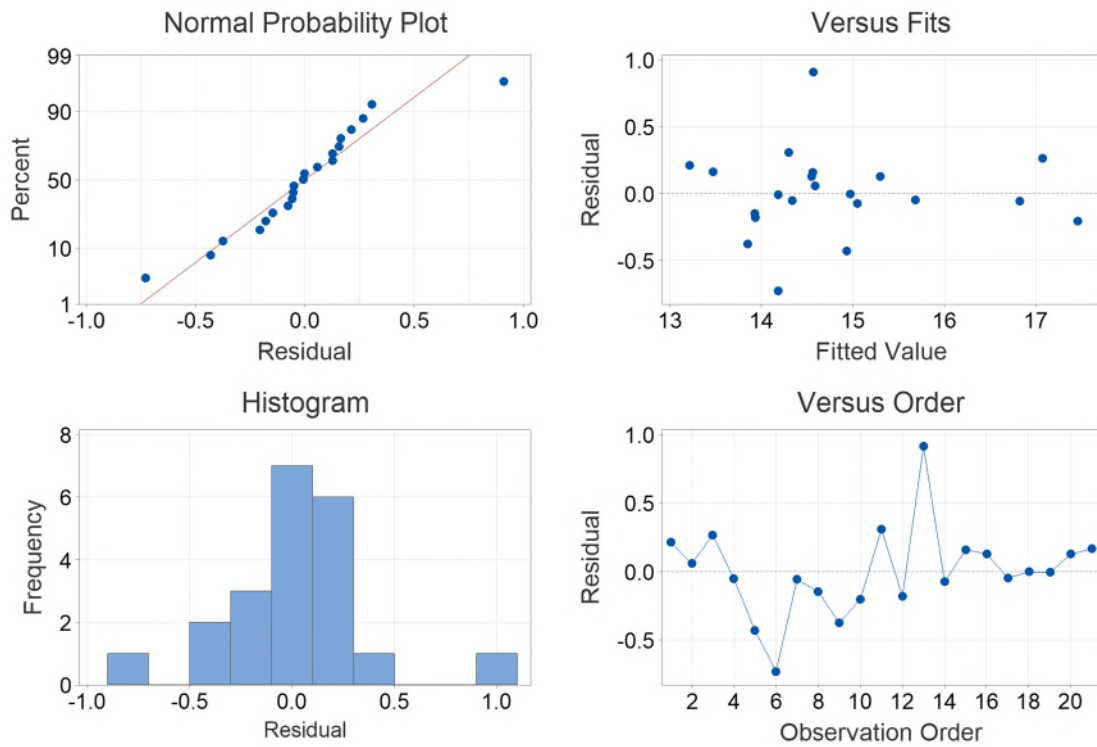
It can be seen that the method used to determine material thermal diffusivity significantly influences the variability of the obtained values. As shown in Figure 3-15, thermal diffusivity estimates at 2.4 kJ exhibited greater variability when using Parker's method compared to NLSF. In contrast, at 4.8 kJ and 9.6 kJ, the estimated values remained more consistent across all thicknesses. However, at the largest thickness (9.87 mm), Parker's estimates are more consistent throughout all energy levels. The disparity in measurements using NLSF at lower energies and higher sample thicknesses could be attributed to its consideration

of the entire back wall temperature curve rather than a single value, as in the Parker method, making it more susceptible to noise in the acquired signal, which translates to a higher disparity in the thermal diffusivity measurement. The reduced SNR due to lower excitation energy translates to a higher disparity in thermal diffusivity measurements. However, in terms of precision, the NLSF still outperforms Parker, especially at lower thicknesses and higher energy levels.

Figure 3-16 shows the residual plots of the thermal diffusivity measurements using both NLSF and Parker for the laboratory experiments. Comparing the plots to what was observed in the FEA model, similar conclusions can be drawn. Both FEA and laboratory experiments display normal distribution and show no indication of any bias that may have affected the measurement of thermal diffusivity. Furthermore, it can be seen that this behaviour is exhibited regardless of the method used to estimate thermal diffusivity. This demonstrates that the methodology employed in this research is a bias-free approach to thermal diffusivity measurement, effectively achieving the objective of establishing a simple step-by-step procedure that can be easily replicated for measurements in the transmission mode. Contrary to what is observed in the FEA analysis (Figure 3-9) comparing the residual values in Figure 3-16a,b shows that the variability in the estimated values is halved when the NLSF algorithm is chosen to evaluate thermal diffusivity (0.5 using NLSF and 1.0 using Parker's half-rise method). This implies that the NLSF algorithm offers more precise estimates for thermal diffusivity. The FEA model plots display lower residual values compared to the laboratory experiments, which is expected due to the reasons previously mentioned. Moreover, in the simulations, both methods display similar values for the residual.



(a)



(b)

Figure 3-16 Residual plots from laboratory experiments for estimating thermal diffusivity using (a) NLSF and (b) Parker.

3.5 Conclusion

While the through-transmission measurement technique for PT has been around for a long time, it has not seen significant developments compared to the reflection mode. A major obstacle hindering the technique's development is its inability to quantify defect depth, even though it is able to detect deeper defects compared to the reflection mode. Moreover, there is a notable absence of theoretical models that accurately describe back-wall temperature behaviour. The literature also lacks a step-by-step guide for conducting through-transmission thermography measurements, especially in the laboratory setting. This study addresses these challenges by employing a full-factorial DOE approach, combining FEA and laboratory experiments to evaluate thermal diffusivity. Thermal diffusivity is estimated using two methods: the NLSF and Parker's half-rise equation. The ability to accurately estimate thermal diffusivity and corresponding measurement uncertainties is compared. Overall, a simple and repeatable methodology that can be easily replicated in laboratory settings without the use of expensive commercial equipment is presented. Moreover, the introduction of multiparameter optimisation using the NLSF method allows for a more accurate estimation of thermal diffusivity as it removes some of the assumptions for certain parameters that Parker makes. One of these assumptions is that the reflection coefficient $R = 1$, which might not always be the case in a practical setting. While these parameters are difficult to measure in real life, they are crucial in accurately assessing the thermal behaviour of materials. The implementation of DOE is crucial because, although the proposed NLSF algorithm provides more accurate and repeatable results, it is essential to demonstrate that these results are unbiased. The key findings of this research are listed below:

- Parker's method exhibits higher levels of accuracy when estimating material thermal diffusivity at higher thicknesses. In contrast, the NLSF algorithm offers similar levels of measurement accuracy regardless of the material thickness (See Section 4.4.1).
- The NLSF algorithm is a more robust method for estimating material thermal diffusivity compared to Parker's method. This is

demonstrated by adding noise to the temperature signal obtained from the FEA model. At extremely low SNRs, i.e., -20dB , the NLSF offered a significantly lower measurement error value ($\approx 60\%$) compared to Parker ($\approx 1600\%$) (See Section 4.4.1).

- The NLSF algorithm demonstrated repeatable results ($\text{CV} < 4.3\%$) compared to Parker's method ($\text{CV} \approx 7\%$). Additionally, the NLSF exhibited a positive correlation with increasing excitation energy in terms of measurement repeatability, whereas Parker displayed no such trend (See Section 4.4.2).
- From this research, several key factors such as NETD, material homogeneity, and measurement repeatability influence the thermal diffusivity measurement in the real world as opposed to simulations. These factors are not considered in the FEA model, which has led to disparities in thermal diffusivity measurement, as demonstrated by the comparative analysis of FEA and laboratory experiments (See Section 4.4.3).
- Finally, it has been observed in experimental conditions that the choice of algorithm affects the variability in the thermal diffusivity estimates. The variability in thermal diffusivity estimates is halved by choosing NLSF instead of Parker. However, this effect is not present in the simulations (see Figure 3-9 and Figure 3-16). This makes the NLSF algorithm a more attractive candidate for conducting thermal diffusivity measurements.

These findings are crucial to obtaining a comprehensive understanding of through-transmission thermography for thermal diffusivity measurements. Furthermore, the insights from the comparative analysis between FEA and laboratory experiments pave the way for a potential correction factor that can be implemented to reduce the current disparity. However, due to the volume of results presented in the study, the implementation of a correction factor has been planned for a future study. The incorporation of a correction factor in simulation models can significantly enhance the accuracy of material thermal behaviour modelling, enabling more effective prognostics and preventive strategies to

mitigate failure. This advancement could lead to a substantial reduction in resource consumption and waste generation, thereby contributing to a more sustainable and environmentally friendly approach within the industry.

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4 Depth quantification using through-transmission PT

Defect depth estimation using through-transmission pulsed thermography: A numerical and experimental investigation

Submitted for publication as Ali, Z.; Addepalli, S.; Zhao, Y Defect depth estimation using through-transmission pulsed thermography: A numerical and experimental investigation.

Abstract

Through-transmission pulsed thermography is widely recognised for offering higher defect resolution than reflection mode, yet its development has been hindered by challenges such as quantifying defect depth. This study addresses the depth quantification gap by introducing a novel depth estimation technique based on the relationship between defect depth and the Fourier number. The method is validated through both finite element modelling and laboratory experiments using calibration samples with embedded air-gap defects at known depths. Results show that depth estimation accuracy improves as defects approach the backwall, consistently across both simulation and experimental environments. Finite element analysis also demonstrates that the proposed technique outperforms the log second derivative method typically used in reflection mode. These findings advance the capability of through–transmission thermography for precise subsurface defect characterisation.

Keywords: through–transmission; pulsed thermography; one-dimensional heat transfer; infrared thermography; defect depth; effective thermal diffusivity; finite element analysis

4.1 Introduction

The advent of additive manufacturing (AM) processes during the third industrial revolution in the 1980s paved the way for revolutionising various industries such as the construction industry [191]. The process involves creating objects from data obtained by 3D models, using a layer-by-layer printing process as specified by ASTM F2792 [192]. As a manufacturing technique, AM offers several

advantages over traditional methods. Some examples include rapid prototyping, reduction in repair times, reduced labour cost, production of complex geometries, improved quality, and decentralised manufacturing. While the technique has been around for more than 30 years, it was only after the last major patent for fused deposition modelling (FDM) expired in 2009, that interest for AM technologies was reignited [193]. As of 2024 the additive manufacturing market is evaluated at USD 22.5 billion, with the market size expected to reach 180.6 billion by the year 2036 [194].

The rapid popularity of AM has been primarily driven by the automotive and aerospace industries [28]. This is due to the possibility of manufacturing structures that are lightweight, thereby reducing the cost of fuel. However, in safety-critical industries like aerospace, every component must undergo rigorous testing to detect structural defects that could compromise safety. Economically, testing should not reduce functionality, as this would increase rebuild costs. Undetected flaws in AM parts can lead to catastrophic failure. The most common defect types for powder-based AM parts included delamination, dislocation cells, internal cracks and pores, and surface cracks [195]. These concerns raise the demand for a practical and reliable non-destructive technique (NDT) that can accurately assess the structural integrity of a component. For AM, the current leading NDT technique is Computed tomography CT [28]. However, the technique does have several disadvantages such as cost, longer inspection times, and complex post processing of CT data. Moreover, a major drawback of CT is the requirement of structures to have symmetric bodies with revolution shapes such as spheres and cylinders [196]. This has prompted researchers to explore alternative NDT techniques such as infrared thermography (IRT).

4.1.1 Infrared thermography (IRT)

Infrared thermography has gained rapid popularity in recent years as an effective non-contact/non-intrusive NDT technique to assess various materials. Pulsed Thermography (PT) which a subset of IRT has become an established technique for assessing various materials ranging from traditional metallic components through to advanced materials such as Carbon Fiber Reinforced Polymers

(CFRPs), advanced superalloys and ceramics which have becoming increasingly popular in the aerospace industry due its large strength and its stiffness-to-weight ratios [4,197].

In the context of assessing additively manufactured parts, PT offers several advantages over CT. Pulsed thermographic inspections can be conducted very quickly with inspection times lasting in the order of a few seconds. Secondly, the inspection method is cheaper compared to CT. Thirdly, PT does not require a full 360° access to the part and finally PT does not rely on ionising radiation making it a safer method of inspection. However, like all NDT methods PT does have several limitations. One of the main limitations is its penetration depth, in other words, the ability for deeper defects to be characterised using the surface temperature measurement over a set period of time. Currently the most extensively researched configuration of PT is the reflection mode. In this configuration the IR radiometer and the external heat sources are placed on the same side of the object under testing. While the reflection mode exhibits great defect detection capabilities for surface/near surface defects, its accuracy significantly reduces when the defects are deeper in the object. For CFRPs, Maierhofer et al. determined that for a step sample with various thicknesses ranging from 1.4mm to 5.4mm, the maximum thickness that the reflection mode can reliably detect was 3.3mm [4] with a minimum aspect ratio of 2.

A major drawback of the reflection mode is its sensitivity to noise, which hinders the accurate determination of the thermal diffusivity [198]. The thermal diffusivity is an intrinsic material property that governs how quickly heat will propagate through the material due to an induced temperature difference. Another configuration that has shown to offer reliable thermal diffusivity measurements is the through-transmission configuration. This configuration places the IR radiometer and the external heat sources on opposite sides of the object. Moreover, in terms of defect detection, the transmission mode has demonstrated that it can detect deeper subsurface defects while also offering greater lateral resolution [4,10]. However, its current inability to quantify defect depths has proven to be a major obstacle for further technique development [14]. Current

research trends indicate that pulsed thermography is primarily applied to defect characterisation and inspections where access is limited to one side, making reflection mode the most extensively studied configuration. It is important to note however that for determining material thermal diffusivity, the transmission configuration is still the preferred method of choice and is used in commercially available instruments such as the LFA [150].

4.1.2 Knowledge contribution of this study

This study builds on previous work [13] by investigating subsurface defects using both FEM modelling and experimental validation. A steel sample with defects at varying depths is first modelled under pulsed heating. Physical samples are then fabricated by drilling holes at different depths and sealing them with matching steel plugs, leaving a 1 mm air gap to simulate subsurface porosity. To the best of current knowledge, and until the time of writing, this novel design had not been previously attempted. Existing methods typically use low-conductivity inserts, which do not accurately mimic the thermal behaviour of air. In additive manufacturing (AM), porosity essentially air gaps within parts acts as a key defect, often initiating fatigue due to localised stress concentrations. Higher porosity levels can drastically reduce fatigue limits in AM composites. Therefore, controlled air-gap defects offer a more representative calibration standard for assessing IRT sensitivity to subsurface features. This study introduces a novel approach for quantifying defect depth in transmission mode via a correlation between the Fourier number and defect depth, with accuracy benchmarked against reflection mode using the log second derivative method in FEM. The Fourier number can be defined as the ratio of heat conducted through a material to the amount of heat stored within that material during transient (non-steady state) conditions. While the use of the Fourier number to characterise defects of different sizes is not a new concept and has been employed in previous studies, [198,199] its application has not been explored in great detail, particularly in the transmission mode. Moreover, the proposed method will also be used to quantify uncalibrated damage in CFRPs that have undergone impact testing. Since the defects are uncalibrated i.e., the exact defect dimensions are unknown, the

proposed method will be used to quantify impact damage instead. For the steel sample, the strong agreement between FEM and experimental results highlights FEM's potential as a powerful tool for simulating complex, hard-to-replicate defect scenarios, advancing the precision and applicability of through–transmission thermography in real-world inspections.

4.2 Theory

The purpose of this section is to familiarise readers with the fundamental principles of the techniques employed in this study. This understanding will, in turn, clarify the rationale behind the selection of materials and methods used in the development of the technique.

4.2.1 One dimensional heat transfer

Figure 4-1 shows an object which has been subjected to electromagnetic radiation. Here the x-direction is the direction parallel to the sample thickness. Part of the radiation is reflected, and the other two parts are either absorbed or transmitted. For opaque materials, the transmitted radiation is zero. The amount of radiation that is either reflected or absorbed is dependent upon the materials reflection and absorption coefficients respectively. The sum of these coefficients will always equal to 1.

Figure 4-1 also states that the absorbed radiation is equal to the emitted radiation. This is Kirchoff's law of thermal radiation that states the amount of radiation absorbed by an object at any wavelength is equal to the amount emitted provided that the object is in thermal equilibrium.

The equation that governs the temperature distribution within the material is from the classic heat diffusion theory in solids also known as the Fourier equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (4-1)$$

where T is the temperature (K), t is the time (s) $\alpha = \frac{k}{\rho C}$ is the *thermal diffusivity* of the material (m²/s); k is the thermal conductivity (W/mK); ρ is the density (kg/m³); and C is the specific heat (J/kg K).

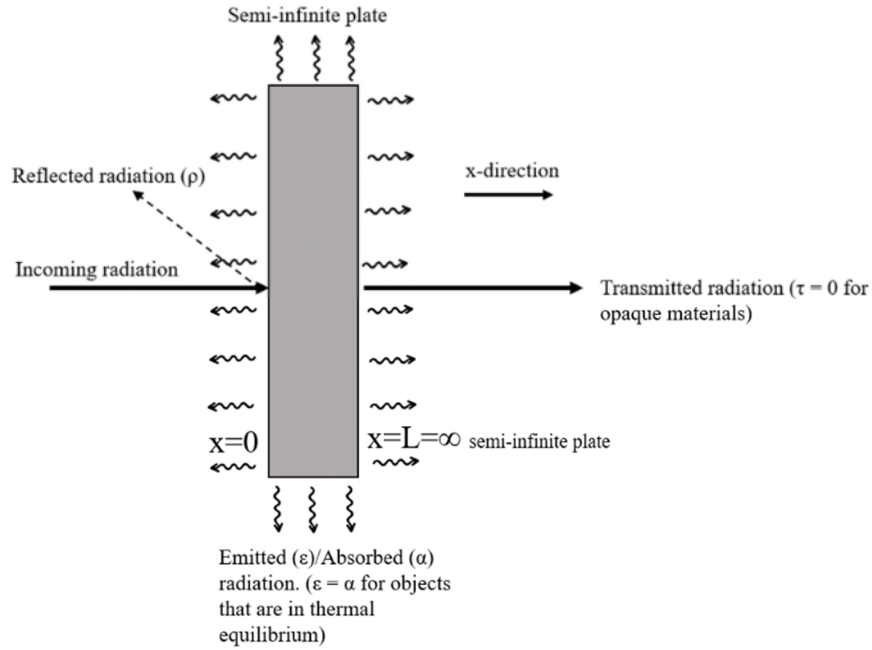


Figure 4-1 Schematic describing an objects response to incoming electromagnetic radiation (Image created on Microsoft Powerpoint)

4.2.2 Pulsed thermography

For pulsed thermography, Parker et al. employed the one-dimensional heat transfer equation developed by Carslaw and Jaeger [65], addressing several challenges associated with obtaining analytical solutions [12]. Firstly, the issue of thermal contact resistance was mitigated through the use of flash heating. Secondly, surface heat losses were minimised by acquiring thermal measurements over a very short duration in the order of milliseconds. This resulted in the following equation:

$$T(L, t) = \frac{Q}{\rho CL} \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp \left(-n^2 \pi^2 \frac{\alpha t}{L^2} \right) \right] \quad (4-2)$$

where L is the sample thickness (m) and Q is the excitation energy (J/m^2). Two dimensionless parameters V and ω can be defined to make the equation independent of specific material properties and therefore Equation (4-2) can be re-written as:

$$V(L, t) = \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp(-n^2 \omega) \right] \quad (4-3)$$

where $V = T/T_M$ in which T_M is the maximum temperature that the backwall can reach and $\omega = \pi^2 \frac{\alpha t}{L^2}$ is the dimensionless time quantity. The equation describing the front wall temperature response is the same as in Equations (4-2) & (4-3) without the $(-1)^n$ term.

To find the thermal diffusivity of the material, Parker introduced the half-rise temperature method where in the time taken to reach half the maximum temperature is recorded. Using the previously defined dimensionless parameters, when $V = 0.5$, then $\omega = 1.38$ since $\omega = \pi^2 \frac{\alpha t}{L^2}$. Thus α can be determined as:

$$\alpha = \frac{1.38 L^2}{\pi^2 t_{1/2}} \quad (4-4)$$

This method is the most accepted, the standard method used for thermal diffusivity estimation for both research and commercial instruments such as the LFA 427 [150].

4.2.3 New least squares fitting (NLSF) algorithm

While Parker's half-rise method is widely used for estimating thermal diffusivity, it has key limitations. As noted by Chihab [87], it overlooks heat losses at the front and back surfaces and requires data acquisition immediately after the flash event ($t = 0$). This is not an issue in reflection mode, where both the flash and IR radiometer are on the same side. However, in transmission mode, shielding is required to prevent direct heating of the backwall, which also blocks the radiometer from detecting the flash event. This can be resolved with a synchronised system that records the flash frame.

Another limitation is the method's assumption of no subsurface defects, implying a thermal reflection coefficient of 1. In reality, as Lau et al. has shown, this value ranges between 0 and 1 [182]. This variation arises because heat transfer across a defect involves material–air–material interfaces, lowering the effective

diffusivity, as described by Maierhofer et al. [4]. Accurate measurement therefore requires adjusting the reflection coefficient in Equation (4-2).

To address these issues Sirikham et al. [181] introduced the new least squares fitting algorithm (NLSF). Improving on the previously introduced Least squares fitting algorithm by Sun [200] which assumed the R to be 1, the authors introduce a new analytical mode as follows:

$$T(t, B, W, R, t_s, s) = \frac{B}{\sqrt{t + t_s}} \left[1 + 2 \sum_{n=1}^M R^n \exp \left(-\frac{n^2 W}{t + t_s} \right) \right] - s(t + t_s) \quad (4-5)$$

where $B = \frac{Q}{\sqrt{(\pi \rho c k)}}$, $W = \frac{L^2}{\alpha}$, t_s is the starting time for sampling, M is a large iteration number, and s represents the slope of the linear portion of the temperature time curve. The addition of t_s is unique in this case as it allows for taking data segments that don't necessarily start at $t = 0$. The *lsqnonlin* function available in MATLAB is used to solve this 5-parameter optimisation problem based on the following relation:

$$\min_{B, W, R, s, t_s} \|\tilde{T}(t) - T(t)\| \quad (4-6)$$

This method has successfully been implemented in the reflection mode but was not used for the transmission mode until recently [13]. Moreover, α is assumed to be known a priori in the equation above. However, as mentioned in Section 4.1, the reflection mode's sensitivity to noise reduces its reliability in measuring the thermal diffusivity which is why the transmission mode needs to be used. The methodology is similar except in this case Equation (4-2) was used. The optimal parameters can be determined in a similar manner to Equation (4-6) as shown below:

$$\min_{W, R, \alpha, t_s} \|\tilde{T}(t) - T(t)\| \quad (4-7)$$

In this case the parameter $W = \frac{Q}{\rho c}$. The 5-parameter optimisation problem has been reduced to a 4-parameter optimisation problem in the transmission mode with α included as one of the unknowns.

4.3 Materials and Methods

Now that the fundamental theory has been covered, this section presents a detailed methodology that has been used to obtain the results. Based on previous work it has already been established that there has been a lack of transparent methodologies that can reliably provide the temporal information required to evaluate thermal material properties [14]. A follow up study addressed this gap by implementing a full factorial design of experiments to observe the effect of changing sample thickness and pulse energy on thermal material property evaluation [13]. This work builds on the conclusions presented previously by examining a sample with subsurface defects at different depths.

4.3.1 Design of experiments (DoE)

In single-input, single-output (SISO) systems, even black-box models allow for a clear relationship between input x and output y , enabling straightforward sensitivity analysis. However, in multi-input, single-output (MISO) systems, the presence of multiple inputs and their potential interactions complicates the analysis. To address this, a structured approach like full factorial design of experiments (DoE) is essential. This method systematically varies inputs to quantify both main and interaction effects, enabling a more comprehensive and accurate sensitivity analysis.

For the purpose of this study, three input factors are considered with three levels. The three factors are the geometric features of the defect. The three levels are the depths at which these defects are located. Table 4-1 shows the different factors (Defect size and shape) and the three levels (Defect depth).

Table 4-1 Input parameters for the sample being inspected

Defect size and shape	16mm diameter circle	8mm diameter circle	16mm length square
Defect depth (mm)	1	3	5

Note that the defect depth is measured from the side which have not been covered by plugs in the actual sample (See section 4.3.3). To remove any confusion going forward in this study, the side without the plugs will be referred to as the “rear side” and the side with the plugs will be the “front side”. In the

reflection mode, thermal excitation is applied to the rear side, whereas in the transmission mode, it is applied to the front side. The sample dimensions were set to 150 × 100 × 8 mm, following a previous study that used specimens of comparable size [173]. These depths were chosen to span the full range of interest, allowing for the evaluation of thermal behaviour at both shallow and deep locations within the material. This ensured that the pulsed thermography analysis captured how defects at varying depths, both near the surface and further beneath it affect the captured thermal response.

For the defects two circles with a height of 1mm and different diameters are chosen to observe the effect of the defect diameter on the temporal response. Earlier research [142] had indicated that the defect size had a greater influence on the temperature contrast i.e., the temperature difference between the defect and defect-free areas. However, that study did not perform physical experiments. Moreover, the type of DoE conducted was a Taguchi design and not a full factorial design. While Taguchi offered a more practical DoE protocol, it did not perform as well a full factorial design [201]. Furthermore, the study by Ali et al (2023) also revealed that the shape of the defect influences the temperature contrast [142]. For 3 factors at 3 levels, a full factorial design will have a total of nine runs as shown in Table 4-2. Since all the defects are on the same sample, the temperature information from each zone can be acquired from a single data capture.

Table 4-2 Number of experimental runs for a full factorial DoE

Run	Defect size and shape	Defect depth in mm (as measured from the backwall)
1	16mm length square	3
2	8mm diameter circle	5
3	16 mm diameter circle	3
4	16mm length square	5
5	16 mm diameter circle	5
6	8mm diameter circle	3
7	16mm length square	1
8	8mm diameter circle	1
9	16 mm diameter circle	1

4.3.2 Finite element modelling

To simulate pulsed thermography on a sample with subsurface defects, the heat transfer module in COMSOL (v.6.0) was used. First a stainless steel 304 plate was created using the in-built CAD module. The dimensions of the plate were set to 150mm x100mm x 8mm in-line with the manufactured sample. The motivation for choosing stainless steel was that it was the material that will be used in the experimental part of this study (See section 4.3.3) so that a like-to-like comparative analysis can be undertaken. All the defects were modelled as air gaps embedded within the same plate making up to a total of nine defects.

For the mesh, the geometry was partitioned so that only the defect-zones can be finely meshed. To record the temperature information for the sound area, a small region at the top of the plate (15x15mm) was partitioned for the fine mesh. The rest of the geometry had a coarser mesh. The justification behind finely meshing parts of the geometry and not the whole geometry is to save computational time. For the 16mm diameter circle and 16mm length square defect, the area that was finely meshed was a 25x25mm square and for the 8mm diameter circle the area was 15x15mm square. The reason for choosing these areas slightly greater than just the defect areas is to avoid any edge effects that might adversely affect the boundaries of the defect which would have otherwise had a fine mesh inside and a coarser mesh outside. For the fine mesh, the element size was gradually reduced until further refinement produced no noticeable change in the resulting temperature profile. This confirmed that the solution had reached mesh independence.

Figure 4-2 illustrates the finite element model. The red regions in Figure 4-2a are the defects and the green regions are the ones where the surface temporal information has been extracted from (both front and back walls). Figure 4-2b shows the meshed geometry showcasing the regions of fine and coarse mesh.

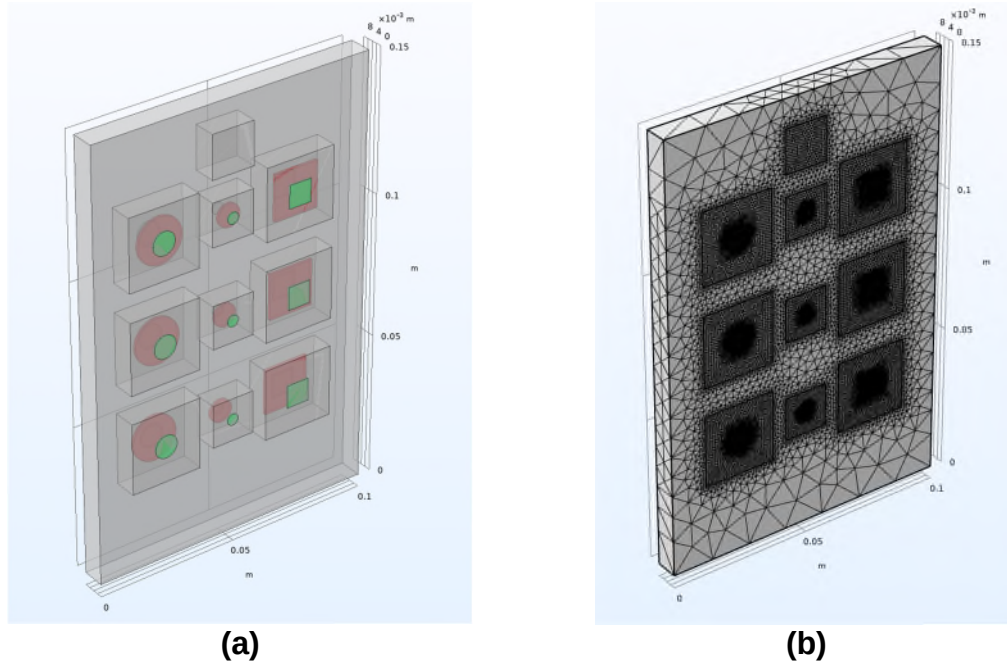


Figure 4-2 Geometry created in pulsed thermography of a stainless steel 304 plate with subsurface defects a) the red regions are the defects, and the green regions are the area from which the surface temporal information was extracted b) the meshed geometry with a finer mesh in the regions from which the temperature information was extracted and coarser mesh elsewhere to save computational time

While there have been previous finite element models that have simulated pulsed thermography [116,164], they have focused only on the reflection mode. Moreover, they do not delve into the details of how the simulation is setup which makes it slightly challenging to recreate the model. For this reason, Table 4-3 inspired by Vora et al. [179]. has been created to provide more transparency for the FEM. Lastly for the time step, it was set to 0.02s to mimic the frame rate of the IR camera.

Table 4-3 Input parameters for the finite element model on COMSOL

Thermal material properties	
Specific Heat Capacity (J/kg.K)	500
Density (kg/m ³)	7930
Thermal Conductivity (W/m.K)	16.2
Plate Geometry	
Height (mm)	150
Width (mm)	100

Defect size and shape	16mm diameter circle, 8mm diameter circle, 16mm length square
Defect Depth (mm)	1, 3, 5
Heat Transfer Physics	
Initial Temperature (K)	293.15 (Applied to the entire body)
Pulse energy (J)	500
Pulse Width (ms)	2
Heat flux q_0 (W/m ²)	$((\text{Pulse Energy}/\text{Pulse width})/(\text{Width}*\text{Height}))*B(t)$
Convective heat transfer coefficient h (W/m ² .K)	5
Emissivity ϵ	0.95
Meshing Parameter (area of interest)	
Mesh size (uniform in all directions including through thickness)	Extremely fine
Maximum element size	0.001
Minimum Element size	0.00001
Maximum Element growth rate	1.3
Curvature factor	0.2
Resolution of narrow regions	1
Meshing Parameter (rest of the geometry)	
Mesh size (uniform in all directions including through thickness)	Normal
Maximum element size	0.015
Minimum Element size	0.0027
Maximum Element growth rate	1.5
Curvature factor	0.6
Resolution of narrow regions	0.5

4.3.3 Experimental work

For the laboratory experiments, a control sample made from steel and a carbon composite laminate both with defects were identified, their specifications are summarised in the subsections below.

4.3.3.1 Steel Samples with subsurface airgap defects

For the physical experiments, first a 3D CAD model of the stainless steel 304 sample was developed. A substrate with holes would need to be machined. These holes will be plugged in by metallic plugs of the same material. The depth of the plugs has been designed such that they would completely enclose the holes in the substrate leaving a 1mm ($\pm 0.01\text{mm}$) air gap at different depths for the various defects machined in the substrate regardless of their lateral size. The fabrication process for the steel substrate and plugs was carried out in Langstone

Engineering Ltd, which is a company based in Portsmouth, United Kingdom. The dimensions for the substrate and the plugs were manufactured with tolerances specified by ISO 286 standards [202]. Figure D-1 in Appendix D shows the CAD model of the substrate and the plugs that were used to plug the holes in the substrate. It is important to note that all the dimensions used for the CAD model match the ones used in the FEM so that a like-to-like analysis can be performed. The actual machined samples can be seen in Figure 4-3.

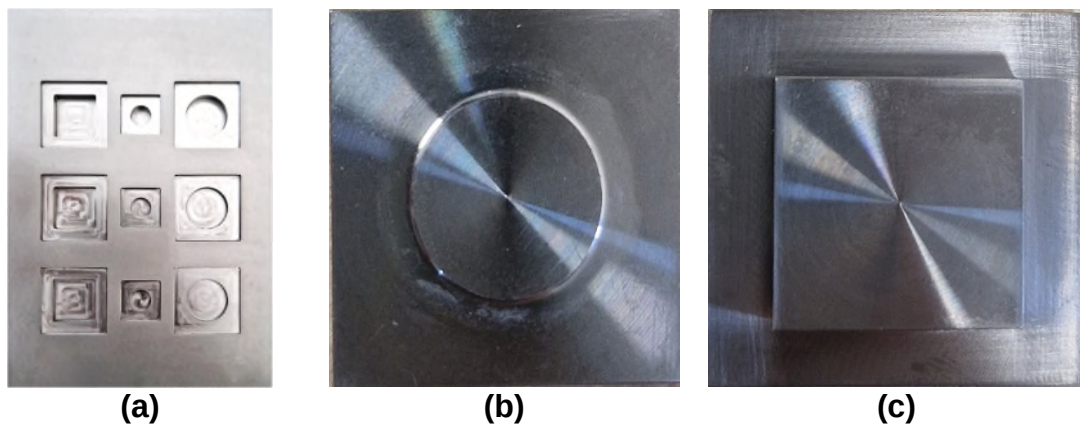


Figure 4-3 Machined substrate based on the CAD model b) Machined plug for the circular hole c) Machined plug for the square hole

4.3.3.2 CFRP samples with impact damage

For the CFRP samples four 750 mm x 750 mm x 3 mm plates that were hand-laid and cured. These plates were then cut into 150 mm x 100 mm x 3 mm smaller samples bringing the total number of samples to 140, 35 samples from each plate. Impact testing with predetermined energy levels was performed on all the samples. Although the samples were impacted at 4, 6, 8, 10, and 12 joules, only a small subset of the 4J, 8J, and 12J energy levels were selected for detailed analysis in this study. This selection was made to ensure a clear and representative distribution across the full range of impact energies exist and can serve as a verification of the developed through-transmission method. It is important to mention that these samples were made for a previous study [69] which had different objectives in terms of knowledge offering. Nine samples were randomly selected from the full set, comprising three samples for each energy

level as repeats. The inclusion of repeats enables assessment of the variability inherent in the manufacturing process of CFRP plates. Although all samples were fabricated under the same standards, slight differences between them are expected. By repeating measurements across multiple samples at each energy level, the analysis can better distinguish true effects of the energy level from random variation, reducing the influence of confounding factors and increasing the robustness of the results. Table 4-4 shows the various samples impacted at different energy levels. The sample ID shows the impact energy (J), plate number (P#) and sample number (S#).

Table 4-4 Impact energy samples with varying levels of impact energy

Sample ID	Impact Energy (J)	Repeat number
4J P1 S2	4	1
4J P3 S25	4	2
4J P3 S27	4	3
8J P2 S11	8	1
8J P2 S13	8	2
8J P2 S15	8	3
12J P1 S21	12	1
12J P2 S21	12	2
12J P1 S22	12	3

The surface subjected to the impact test was designated as the front side, and both the front and back surfaces were monitored by the IR camera in the reflection and transmission configurations as done previously by Maierhofer et al [4]. Therefore, the configurations going forward in analysis will be the same as the ones used in [4] i.e., Reflection Front (RF), Reflection Back (RB), Transmission Front (TF), and transmission back (TB). The CFRP samples with different impact damage can be viewed in Figure 4-4. It was mentioned in a previous study [13] that the peak spectral emission can cause discrepancies in the estimated values for thermal diffusivity. To test this, the entire set of experiments were repeated using a FLIR a655sc longwave camera. A 5x5 pixel circle was created for both the sound and defect areas to capture the temperature information.



Figure 4-4 CFRP samples that have undergone impact damage at energies of 4J (left) 8J (middle) and 12J (right)

4.3.3.3 Pulsed thermography system

For the pulsed thermography inspection system, the IR camera used is the SC7600, a mid-wave camera with an indium antimonide (InSb) cooled detector that has a spectral range of $\approx 1.5\text{--}5.1\mu\text{m}$. For the synchronisation system, an IRT controller from Visiooimage Inc (which is a company based in Quebec, Canada) is used that allows for syncing the flash lamps (also acquired from Visiooimage Inc). The flash lamps can provide variable levels of energies. The pulse duration is dependent on the energy level required and according to the manufacturer it offers 1/175s at 4.8kJ, 1/300s at 2.4kJ, 1/500s at 1.2kJ, 1/900s at 0.6kJ, and 1/1425s at 0.3kJ. For this study the energy delivered from each lamp was set to 4.8kJ giving a combined energy of 9.6kJ for two lamps. The data acquisition was through the FLIR Research Studio software. The camera was triggered externally together with the flash using a MATLAB code that sent a signal to the IRT controller via a telnet server.

The temperature curves in the experiments were obtained from the side of the sample that did not contain plugs (the rear side); in other words, the sides with plugs (the front side) never faced the IR camera. In the reflection mode

experiments, the rear side was exposed to flash heating, while in the transmission mode, the front side was exposed to the flash and the temperature was recorded from the rear. Similarly, in the simulations, transmission mode temperature data were obtained by thermally exciting the front side, whereas for reflection mode, the rear side was thermally excited. For the CRFP sample the flash heating and the subsequent data capture configurations were adopted from previous work conducted by Maierhofer et al. [4]. Figure 4-5 shows the experimental configurations of the reflection and transmission modes. The black sheets were added in the setup to ensure that the flash does not reach the IR camera in the through–transmission configuration.

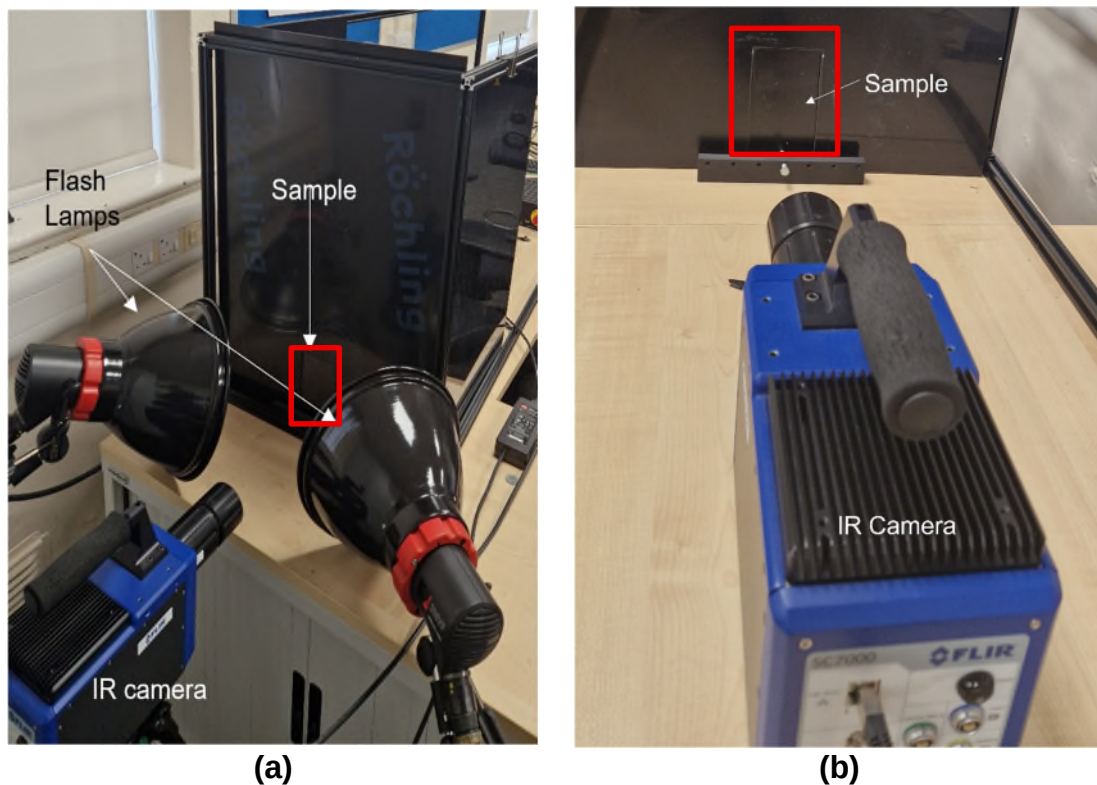


Figure 4-5 Experimental configurations of the a) reflection mode and b) transmission mode

4.3.4 New method for depth quantification in the transmission mode

The current understanding in through-transmission pulsed thermography is that the depth quantification is a challenge since the distance travelled by the thermal wave in the defect and defect free regions is the same [8]. Additionally, exclusive analysis of the temperature contrast curves, as done in [142], shows that they are

influenced by depth. Yet the sensitivity to variations in lateral size is much higher, making these changes easier to distinguish, whereas depth variations are more subtle and therefore more difficult to quantify. Moreover, as it will be shown in Sections 4.4.1 and 4.4.2, effective thermal diffusivity measurements in the defect regions show no clear correlation with defect depth either. However, the thermal property that has been overlooked in depth quantification is the Fourier number, a dimensionless quantity representing a ratio of a material's diffusive rate over its quantity storage rate, calculated using the following equation:

$$Fo = \frac{\alpha t}{L^2} \quad (4-8)$$

where α is the material thermal diffusivity (m^2/s), t is the time in seconds and L is the characteristic length. Existing studies show limited work exploring the variation of the Fourier number with changing defect size and depth [198].

Figure 4-6 shows the step-by-step procedure on how defect depth is estimated using the Fourier number.

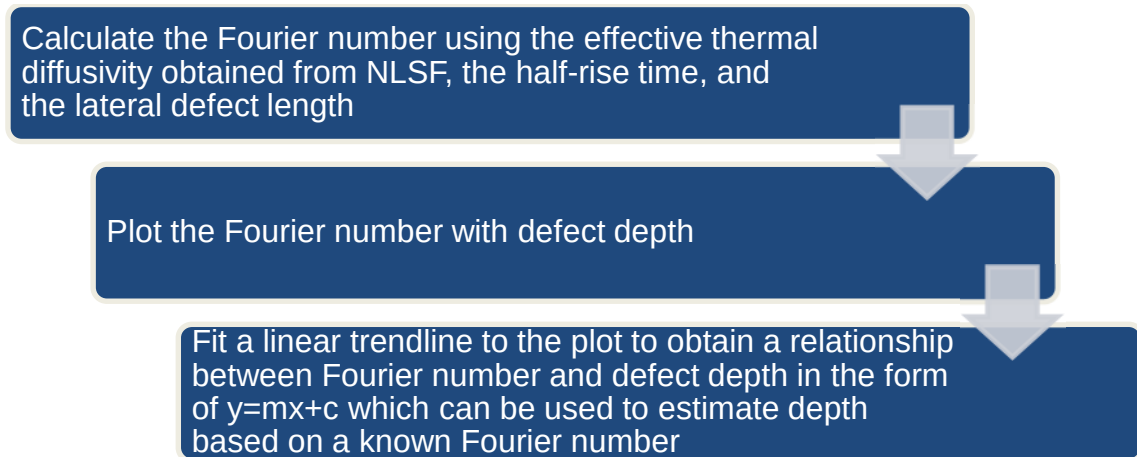


Figure 4-6 A step-by-step procedure to estimate defect depth in the transmission mode

For the purpose of this study, the L was chosen to be the lateral defect length for the square defect and diameter for the circular defects. The justification behind choosing the lateral length can be seen from Table 4-5 where it is observed that the lateral defect size has a greater influence on the effective thermal diffusivity than the defect depth. However, it will be made apparent in the subsequent

subsections that the sensitivity to defect depth is realised through the terms in the numerator of Equation (4-8) i.e., the product of the effective thermal diffusivity α and the half-rise time t which gives us a relationship between the Fourier number and defect depth (L is just a constant that only affects the magnitude of the Fourier number and not its trend with defect depth). The justification for using the half-rise time is based on Equation (4-4) where it is established that the half-rise time is crucial in determining the thermal diffusivity of the material.

4.4 Results and discussion

With the methods and materials clearly outlined, this section discusses the results obtained from following the proposed methodology. First, the results from the FEM are discussed followed by the results obtained in the laboratory experiments. Next a comparative analysis of both FEM and experiments is conducted. Finally, the proposed method's capability in assessing the impact damage of the CFRP samples is discussed

4.4.1 Results from the finite element model

Table 4-5 shows the estimated thermal diffusivity by the NLSF algorithm using the backwall temperature curves and Table 4-6 shows the estimated input energy.

Table 4-5 Estimated thermal diffusivity (sound region) and effective thermal diffusivity (defect regions) using the NLSF algorithm for the sound and defect regions using backwall temporal information

Defect type \ Defect depth	1mm	3mm	5mm
Sound Area (note that defect depth is not applicable for this region)	3.92 (mm ² /s)	3.92 (mm ² /s)	3.92 (mm ² /s)
8mm circle	2.66 (mm ² /s)	2.63 (mm ² /s)	2.94(mm ² /s)
16mm circle	1.47(mm ² /s)	1.38(mm ² /s)	1.48(mm ² /s)
16mm square	1.33(mm ² /s)	1.21 (mm ² /s)	1.29(mm ² /s)

Table 4-6 Estimated input flash energy using the NLSF algorithm for the sound and defect regions using backwall temporal information

Defect type \ Defect depth	1mm	3mm	5mm
Sound Area (note that defect depth is not applicable for this region)	515.47 (J)	515.47 (J)	515.47 (J)
8mm circle	518.78 (J)	520.53 (J)	519.47 (J)
16mm circle	511.89 (J)	518.18 (J)	517.46 (J)
16mm square	510.17 (J)	518.14 (J)	517.32 (J)

Based on theoretical calculations using the material's thermal conductivity, specific heat capacity, and density (Table 4-3), the thermal diffusivity was determined to be 4.09 mm²/s. Although this value is lower than that of air (≈ 22 mm²/s), the much higher thermal conductivity of the material (16.2 W/m·K compared to ≈ 0.026 W/m·K for air) dominates the heat transfer behaviour, resulting in a lower effective thermal diffusivity within the defect region. Consequently, the greater the contrast in thermal properties between the sound material and the air gap or defect, the higher the achievable resolution in thermographic defect detection. The estimated thermal diffusivity in the defect regions is therefore lower, as heat diffusion through the material thickness is reduced due to increased thermal contact resistance and lateral heat spreading around the defects. The term 'effective' is used here as it better represents the diffusivity of the defect regions. [4]. For the sound region, the estimated thermal diffusivity is the materials thermal diffusivity. Comparing the calculated value of the material's thermal diffusivity to the one obtained of the NLSF algorithm results in a 4.2% error. This error can mainly be attributed to the low flash excitation energy and the 0.02s time step for the simulation. Previous work demonstrates that the using a higher excitation energy level and a smaller time step of 0.01s for the simulations yielded errors as low as 0.37% [13]. However, the purpose here was to demonstrate the similarity between the FEM and laboratory experiments which is why a 0.02s time step was chosen to match the frame rate of IR camera that was used to acquire the experimental data. For the estimated energy levels shown in Table 4-6, the input flash energy in the simulation was 500J (to match the energy in the laboratory experiments) resulting in a maximum

error of 4.1% and a minimum error of 2.03%. Figure 4-7 captures this error variation in the different regions (sound and defect areas)

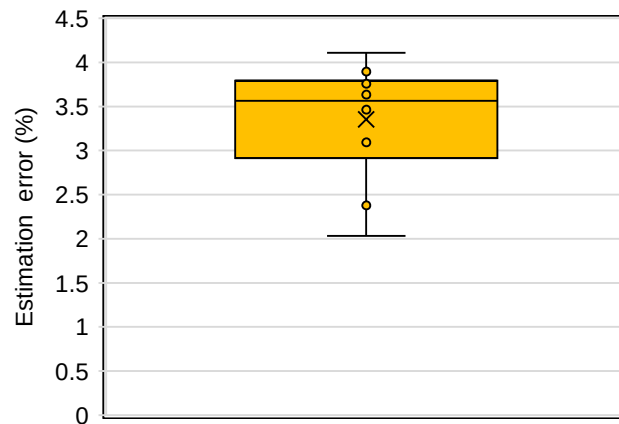


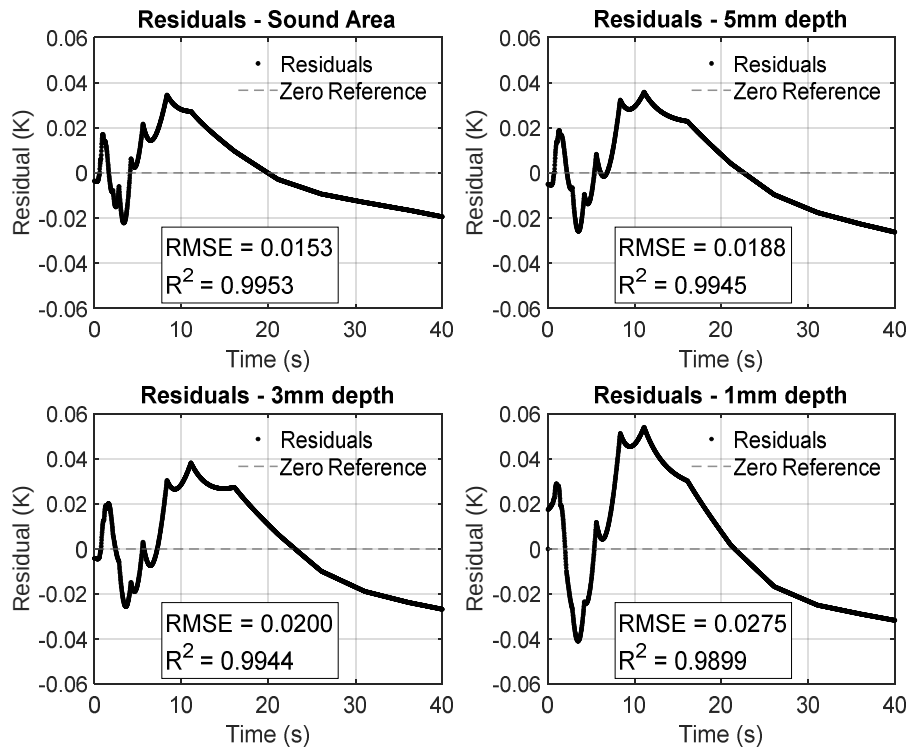
Figure 4-7 Variation of the input energy estimation error in the sound and defect regions

It is important to note that in the transmission mode the front side of the sample was thermally excited (the side with the plugs in the experimental runs). If the depth is measured from the front side of the sample this depth is 6mm. It shows that as the defect gets closer to the backwall the effective thermal diffusivity is higher than when the defect is in the middle of the sample i.e., the 3mm defect. An interesting observation is that the results are consistent regardless of defect geometry. This phenomenon is something that has not been explored in literature and requires further investigation. A plausible explanation will need to consider lateral heat diffusion converting the one-dimensional heat transfer problem into a three-dimensional one.

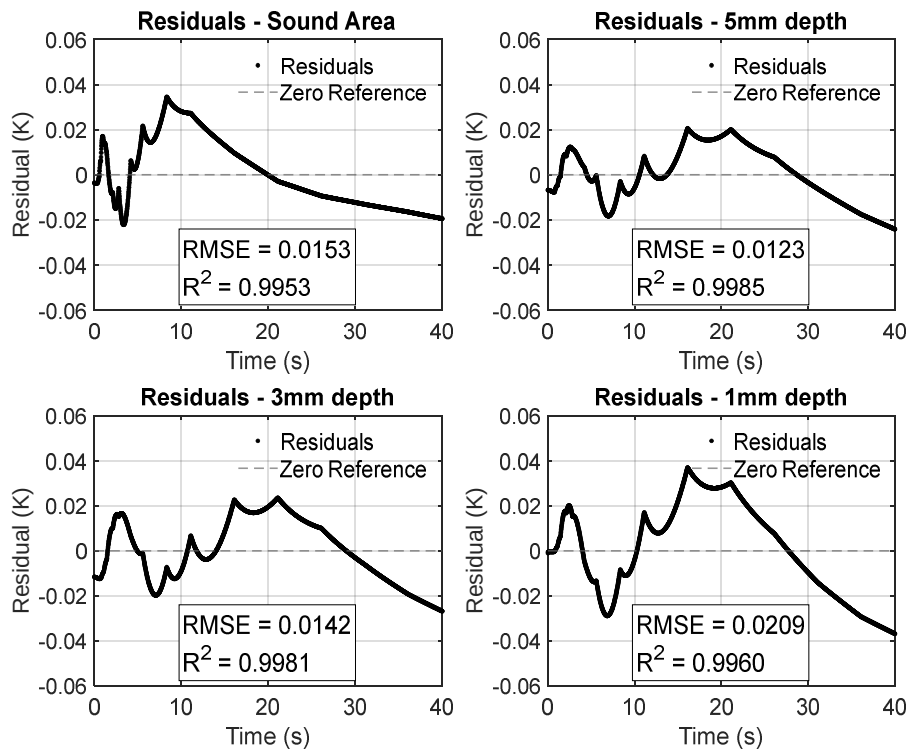
To demonstrate how well NLSF algorithm captures the backwall temperature evolution, a combination of quantitative and visual assessment methods are employed. This analysis is shown in Figure 4-8. Metrics such as the root mean square error (RMSE) and the coefficient of determination (R^2) provide numerical summaries of the fitting accuracy, reflecting the overall discrepancy and the proportion of variance explained by the model. However, these metrics alone may not reveal underlying patterns or systematic deviations. Therefore, residual plots are used in conjunction with RMSE and R^2 to provide a more comprehensive

evaluation. By visualising the differences between the measured data and model predictions over time, residual plots help identify trends, non-random structures, or outliers that could indicate model limitations. A good fit is typically characterised by residuals that are randomly scattered around zero with no discernible structure, reinforcing confidence in the suitability of the NLSF approach for modelling thermal response behaviour.

The fitted curves are in close agreement with the FEM generated backwall temperature curves as indicated by the R^2 value that exceeds 0.99 in each case and the low RMSE value which does exceed 0.0275 for all cases. In terms of the plots, the residuals exhibit minimal drift from the zero reference (represented by the horizontal dashed grey lines in Figure 4-8) and do not indicate any specific pattern i.e., the distribution is mostly random. The residuals do exhibit some random oscillatory motion during the initial heating phase (0–10s) which could be due to some of the assumptions in the FEM model such as the interaction between the boundaries of solid material and the fluid airgap which does not completely align with the theoretical equation used for the fitting (Equation (4-2) assumes that the plate is semi-infinite and defect free), the meshing parameters used, and the time step used for the simulations. During the saturation phase (time ≥ 10 s for the sound area and ≥ 20 s for the defect areas) the theoretical equation slightly overshoots the actual temperature behaviour of the sample hence the decreasing values of the residuals towards the later stage of the simulated values. This is because the simulation exhibits a slight decrease in the backwall temperature profile indicating a gradual cooldown of the sample, something which Equation (4-2) cannot capture.



a)



b)

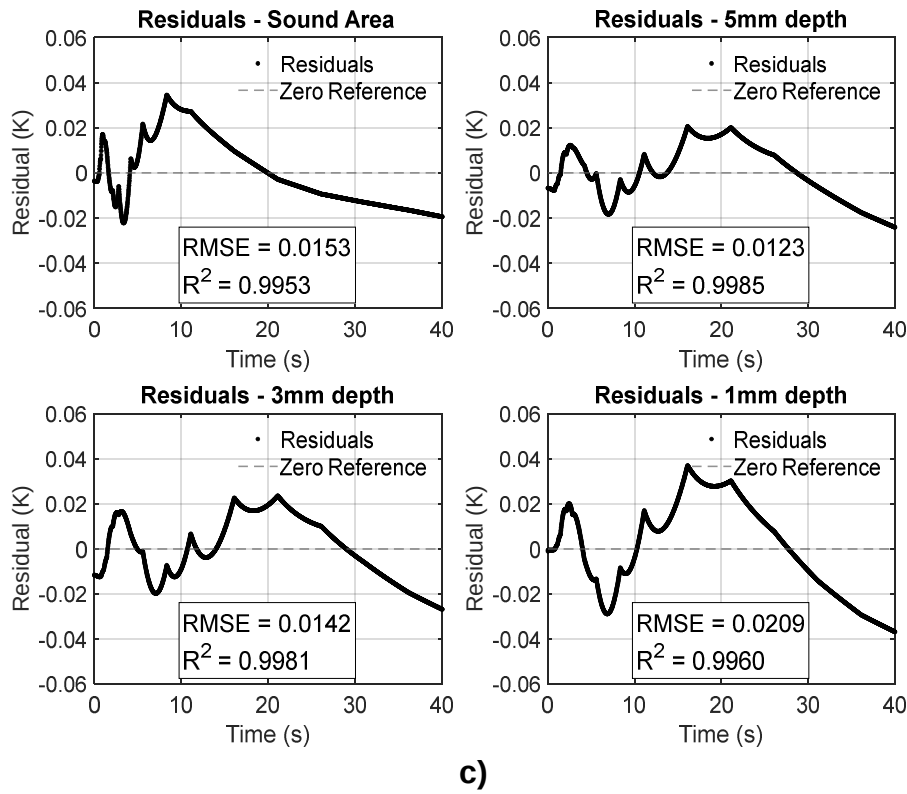


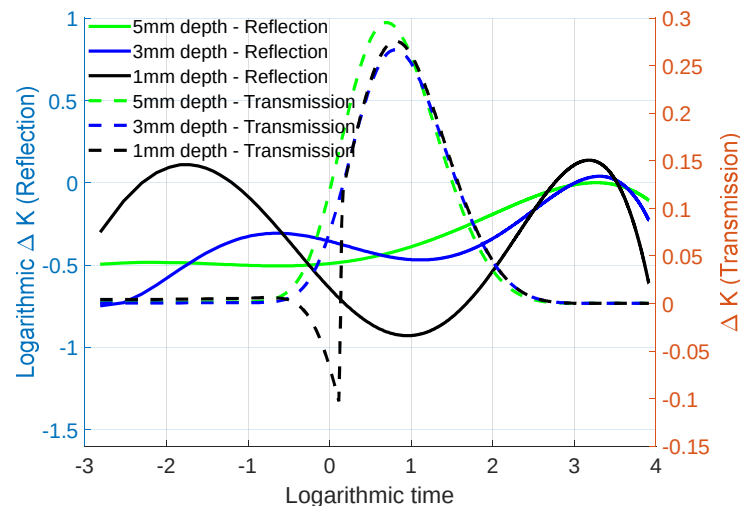
Figure 4-8 Residual plots for the sound and defect regions in the FEM a) 8mm circle defect b) 16mm circle defect and c) 16mm square defect. The horizontal dashed grey line represents the zero reference

4.4.1.1 Dual mode analysis for the FEM

Most of the studies in existing literature either focus solely on the reflection mode or the transmission. Even the studies that explore both modes such as [4] conduct the data analysis of each mode separately. Developing a methodology that combines both the reflection and transmission curves is something that has not been attempted so far. While several reasons can exist explaining this, the most plausible reason could be the lack of calibration samples with fully enclosed defects at known depths. Current methods involve either using flat-bottom hole samples for the reflection mode [203] or adding inserts representing fully enclosed defects [204]. However, until now, no sample has been designed that contains fully enclosed air defects. Since this study addresses this critical challenge, a comparative analysis can now take place. First, the temperature curves of both the reflection and transmission modes need to be processed. For the reflection mode a polynomial fitting of order 6 is applied to obtain a smooth

curve whereas the transmission mode temperature curves use the NLSF algorithm to apply the curve fitting. Next the first derivative plots are generated. For the reflection mode the data is plotted in the logarithmic domain for both the time and temperature and for the transmission mode only the time is in the logarithmic domain. This is done to plot both the curves in a double y-axis plot so that a comparative analysis can be conducted. Figure 4-9 shows the first derivative curves for both the reflection and transmission modes. For the transmission mode the first derivative peaks occur at relatively similar times. This can explain why defect depths are difficult to discriminate in the mode. Moreover, as indicated Table 4-5 by observing the effective thermal diffusivity values, the peak of the first derivative in transmission mode is higher for defects located closer to the back wall.

This indicates that the temperature rise at the backwall occurs at a faster rate in the region where the defect is closer to the backwall. On the other hand, the reflection mode clearly shows distinguishable peaks as the depth changes, with the exception of the 5 mm depth, where the peak is very faint, indicating a depth detection limit for the reflection mode. Analysing both curves individually reveal different limitations. However, observing both peaks that occur in the reflection mode and transmission mode simultaneously reveals an interesting insight. As the defect goes deeper into the substrate the first derivative peak of the reflection mode moves closer to its counterpart in the transmission mode.



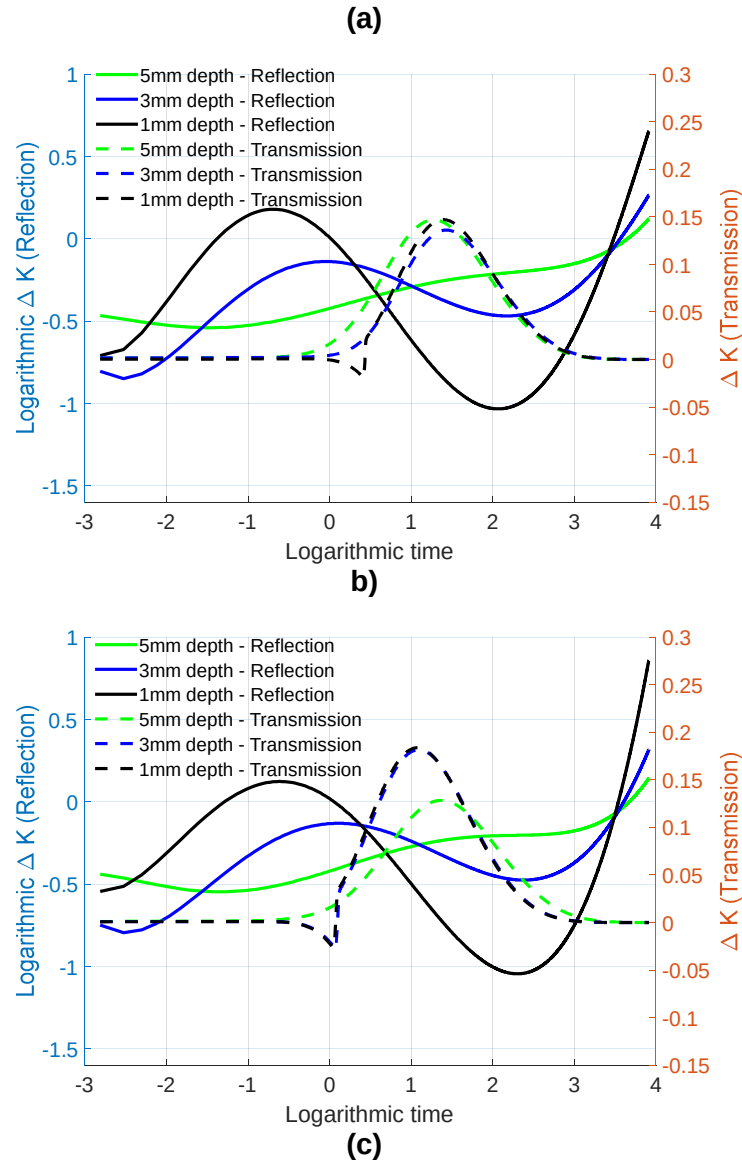


Figure 4-9 Double axis plots for the first derivative of both the reflection and transmission modes. a) 8mm circle defect b) 16mm circle defect and c) 16mm square defect. (Excitation energy is 500J)

The peaks in question here are the first ones that occurs for the reflection mode. As the defect depth moves beyond the detection limits of the reflection mode, the transmission mode is still able to detect it. This means, for achieving a better estimate of the defect location within the sample it would be better to conduct a dual-mode inspection and observe the temporal behaviour of both the reflection and transmission modes.

4.4.2 Results from the laboratory experiments for the steel sample and comparison with FEM

Figure 4-10 presents the raw thermograms acquired in both reflection (4 seconds or 200 frames after flash) and transmission modes (9 seconds or 450 frames after flash) for the steel specimen, which were utilised for temperature data extraction. Defect locations are indicated by black rectangles. A visual comparison of both thermograms reveals that the transmission mode successfully captures all defect features, irrespective of size or depth without the need of any visual enhancement algorithms. In contrast, the reflection mode exhibits limited sensitivity, with defects at 5 mm depth barely noticeable, and those with an 8 mm diameter also exhibiting low detectability.

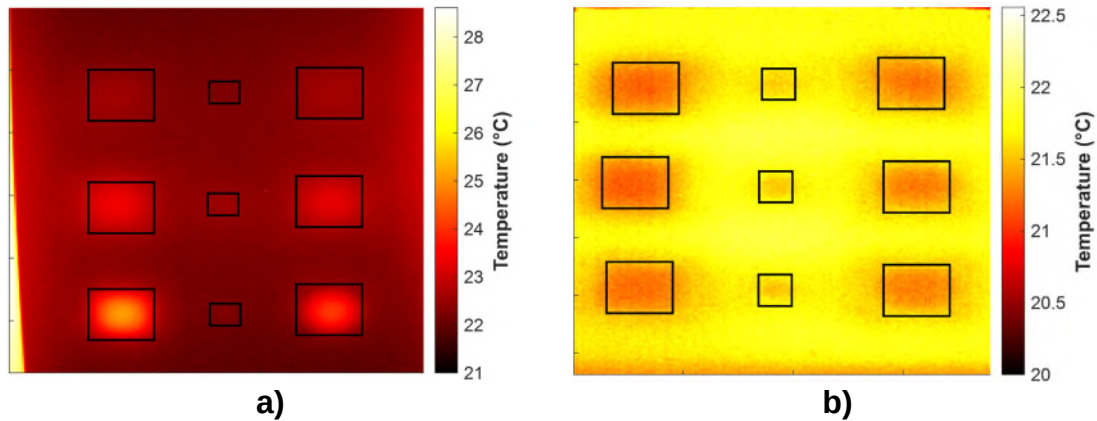
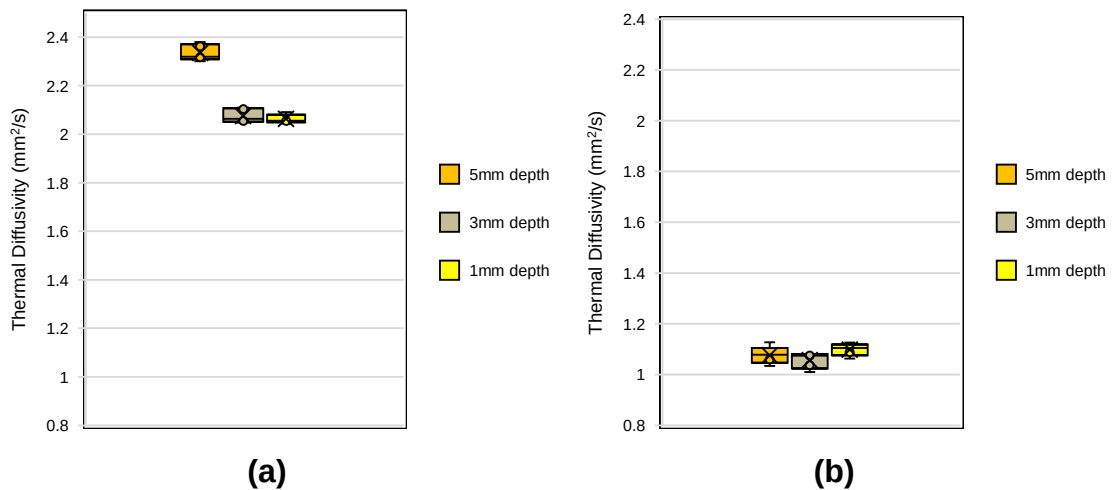


Figure 4-10 Raw thermograms for the steel sample with subsurface defects in a) reflection mode (image taken 4 seconds or 200 frames after flash) and b) transmission mode (Image taken 9 seconds or 450 frames after flash)

Although image processing techniques such as TSR and Pulsed Phase Thermography (PPT) could enhance the spatial resolution and facilitate the detection of smaller and deeper defects especially in reflection mode, their application falls outside the scope of this study. Since the objective was to evaluate the effective thermal diffusivity, the raw thermograms were deemed sufficient due to the adequate temporal information they provided.

For the laboratory experiments a total of five repeats was undertaken for both the reflection and transmission modes to ensure repeatability of the results. This analysis was not performed for the FEM as every run would result in the same values. Figure 4-11 shows the effective thermal diffusivity plots for all the defects

at different depths. The thermal diffusivity of the sound area was not included in these plots as it is much higher therefore making it difficult to see the variation of the effective thermal diffusivities in the defective regions. The temperature information was extracted in a manner similar to the FEM, where the ROI size was set to half the defect area (circular ROIs for circular defects and square ROIs for the square defect), positioned at the defect centre. In terms of pixels, using the conversion factor of 1 pixel = 0.4 mm at a standoff distance of 300 mm, the ROI for the square defect was defined as a 20 × 20 pixel square (corresponding to an 8 × 8 mm area). For the 16 mm diameter circular defect, an ROI of 20 pixels (8 mm) in diameter was used, while for the 8 mm diameter circular defect, the ROI was a 10 pixel (4 mm) diameter circle. The average thermal diffusivity of the sound region was measured to be 3.96mm²/s with a coefficient of variation 0.01% resulting from the 5 repeats. The graphs follow a similar pattern to what was observed in the FEM in terms of the effective thermal diffusivity being slightly higher when the defect was closer to the backwall. The variation in the values can be attributed to the sample not being perfectly homogeneous and the usage of plugs that might have interfered slightly with the heat diffusion through the thickness of the materials.



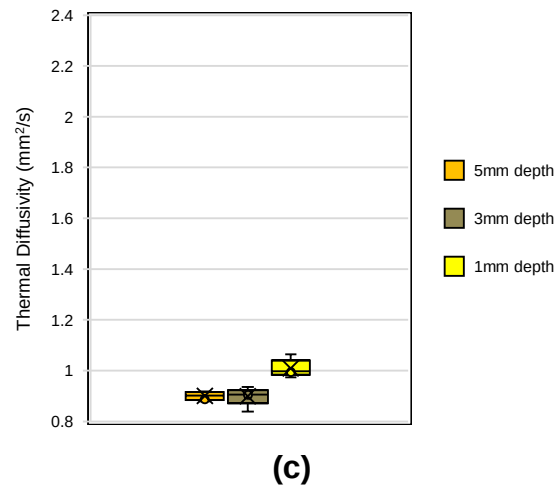


Figure 4-11 Effective thermal diffusivity plots for defects at different depths a) 8mm circle b) 16mm circle c) 16mm square

Another potential source of variation in the results between the FEM and laboratory experiments can be attributed to the uneven heating of the surface. As seen in Figure 4-5, open flash lamps were used. While a lot of effort was taken to minimise this effect by manipulating the position of the sample with respect to the flash lamps and IR camera, Figure 4-12 shows the heating variation in the different regions. To obtain a like-to-like comparison with the FEM, the regions from which the temperature information was extracted was kept the same in the experiments. At a camera standoff distance of 300mm, 1 pixel corresponds to approximately 0.4mm. Using this conversion factor the regions of interest were created for the sound and defect areas. It can be seen that the maximum heat energy was concentrated around the 3 mm deep defects, which were positioned at the midpoint along the vertical axis of the 150 mm high sample. Moreover, it was observed that the minimum heat input occurred in regions where the 1 mm defects were located i.e., at the bottom of the sample. In addition to uneven heating caused by the flash lamps, the reduced energy input at the bottom may also be attributed to the way the sample was secured. A 3D-printed sample holder was used to support the sample, and a metallic screw was employed to fasten it in place to prevent movement. The contact between the sample, the holder, and the screw likely facilitated lateral heat conduction away from the sample, contributing to the lower energy input in that region. Nevertheless, the close agreement with FEM results highlights its accuracy and demonstrates its

potential as a reliable alternative for evaluating material behaviour in cases where defects cannot be readily created experimentally.

Figure 4-13 shows the residual plots similar to the ones generated for the FEM. Similar to the FEM results, an initial oscillatory behaviour is observed during the heating phase, which Equation (4-2) does not capture accurately. However, once the temperature profile at the back wall begins to stabilise, the residuals become centred around zero, indicating a bias-free fit.

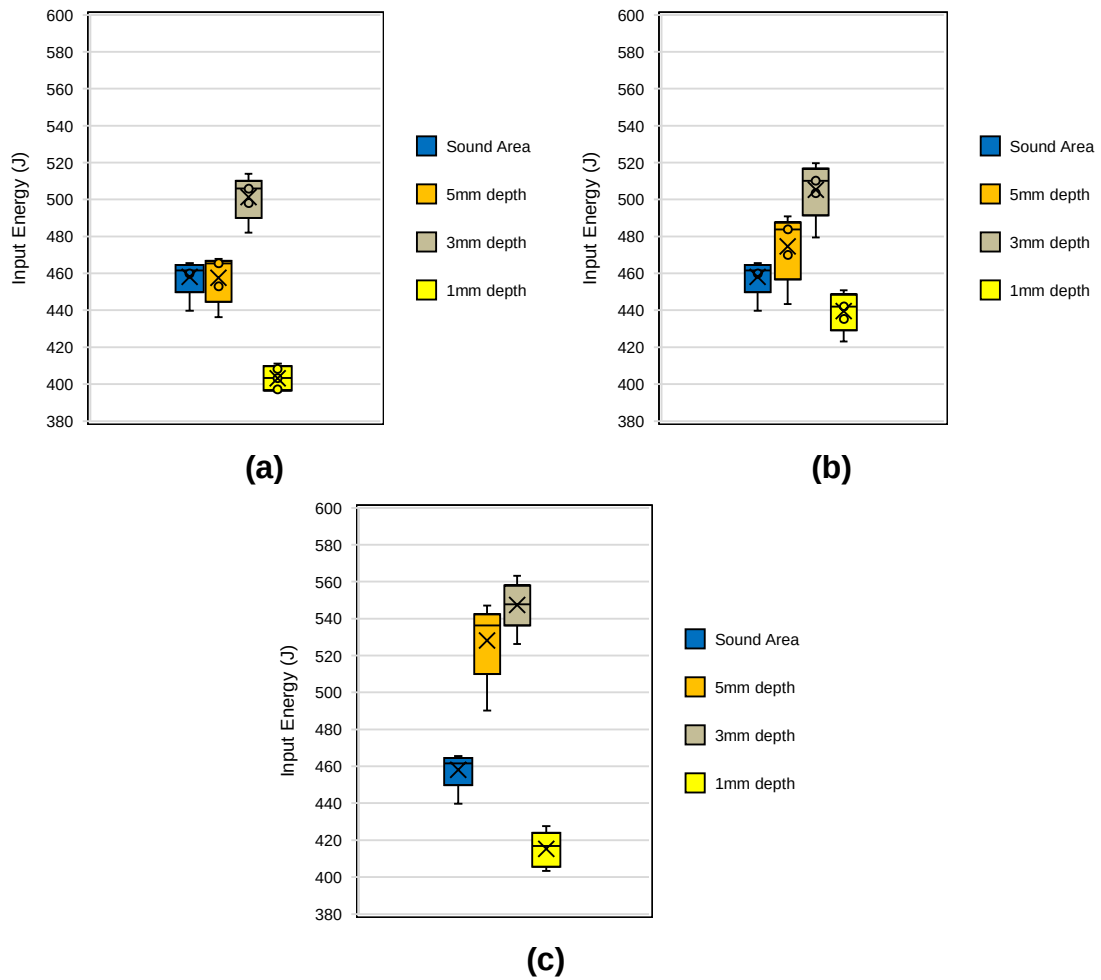
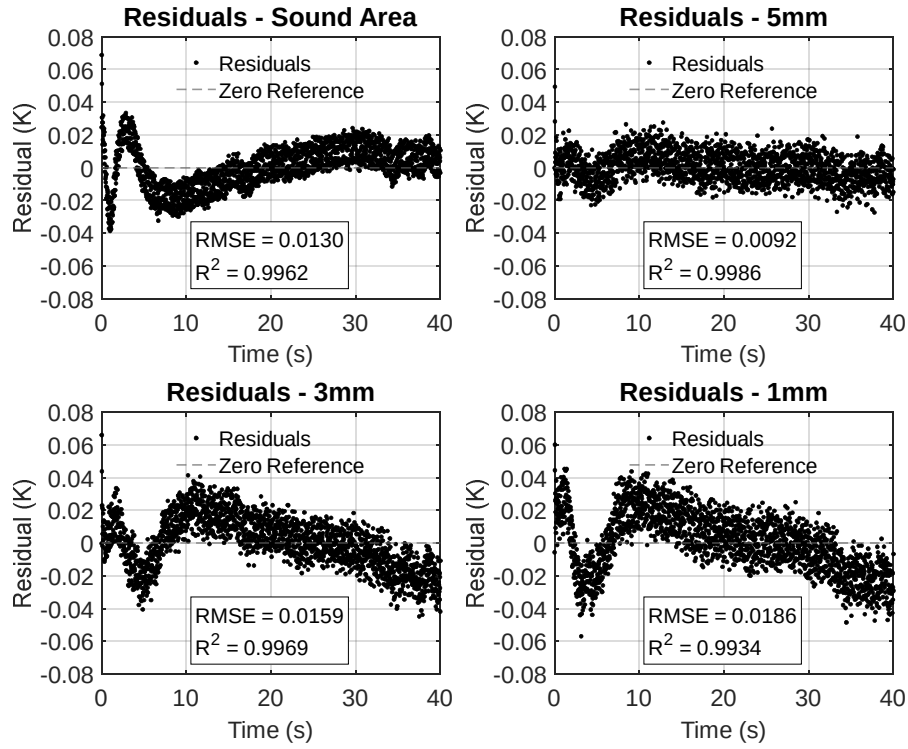


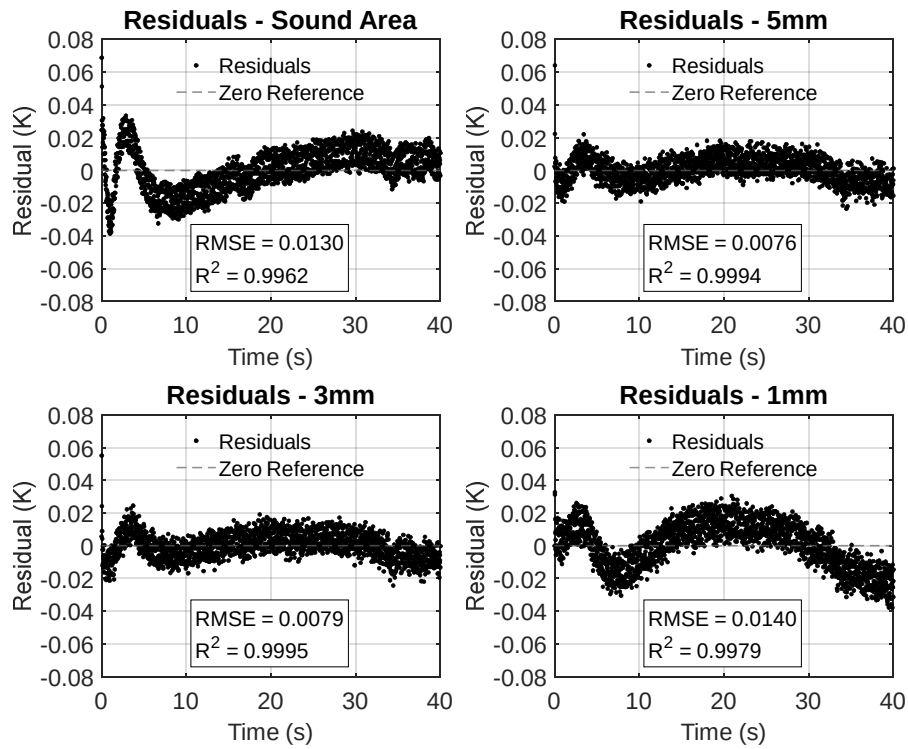
Figure 4-12 Plots showing the heating variation between the sound and different defect regions a) 8mm circle defect b) 16mm circle defect and c) 16mm square defect

Regarding the closeness of fit to the experimental data, all R^2 values once again exceed 0.99, with some plots reaching as high as 0.9994. The RMSE values are also consistently low, with the highest recorded value being 0.0186, suggesting

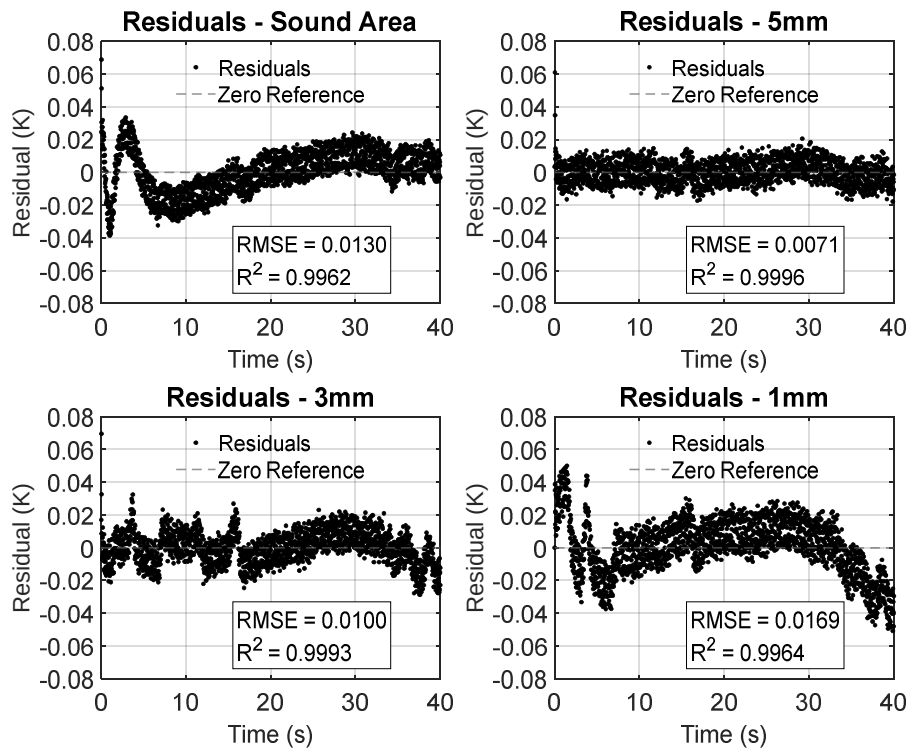
that the NLSF captures the underlying thermal behaviour with a high degree of accuracy. Compared to the FEM results, which yield a single smooth profile, the experimental data exhibit greater dispersion due to higher noise levels. Despite this, the NLSF demonstrates strong robustness, successfully providing accurate fits even in the presence of such variability.



(a)



(b)

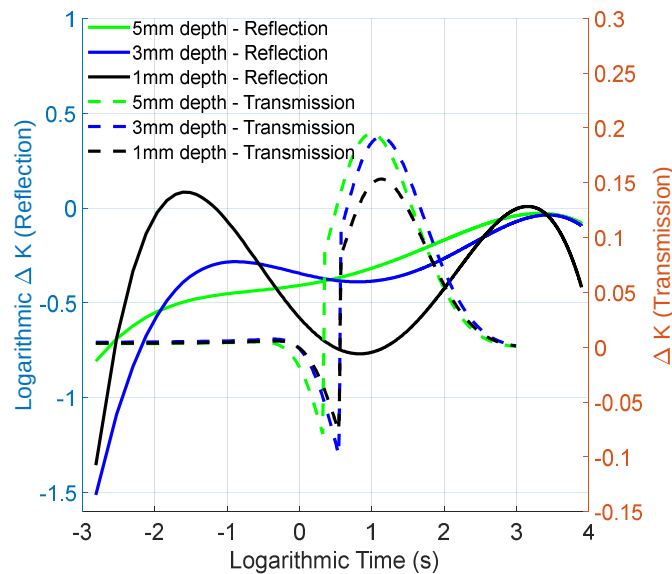


(c)

Figure 4-13 Residual plots for the sound and defect regions in the FEM a) 8mm circle defect b) 16mm circle defect and c) 16mm square defect. The horizontal dashed grey line represents the zero reference

4.4.2.1 Dual-mode analysis for the laboratory experiments

Finally, similar to Figure 4-9, Figure 4-14 presents the first derivative plots from the laboratory experiments. These graphs were generated by averaging temperature values across five runs in both reflection and transmission modes. Analysis of the first derivative curves reveals trends consistent with those observed in the FEM results. Firstly, as with the FEM, the 5 mm depth defects do not produce distinguishable peaks in the reflection mode but do so in the transmission mode. Secondly, as the defect depth increases, the first derivative peaks in reflection mode shift closer to their transmission mode counterparts. A third observation, which also aligns with the FEM, is the sharp drop preceding the transmission mode peaks. This drop is attributed to limitations in the NLSF fitting algorithm, which struggles to accurately model the back wall's thermal response during the initial seconds following the flash event (also indicated by the residual plots in Figure 4-13). As for differences, the timing and magnitude of the peaks differ, likely due to uneven heating and the sample's inherent non-uniform material properties, as well as external variations due to the use of plugs. A comprehensive breakdown discussing the variation between the FEM and experiments can be found in a previous work [13]. However, once again, the similarity between Figure 4-9 and Figure 4-14 further strengthens the FEM's capability to accurately model the temperature behaviour of a defected sample subjected to flash heating.



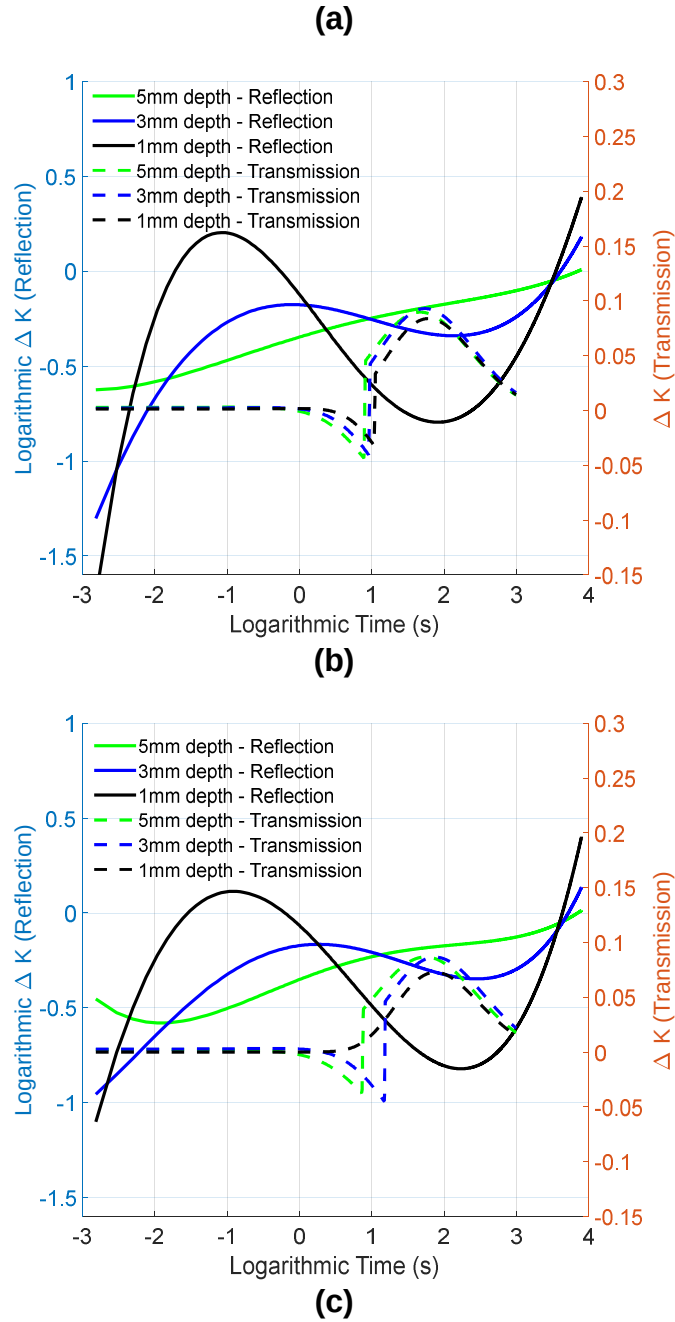


Figure 4-14 Double axis plots for the first derivative of both the reflection and transmission modes obtained from laboratory experiments. a) 8mm circle defect b) 16mm circle defect and c) 16mm square defect.

4.4.3 Depth estimation

4.4.3.1 FEM

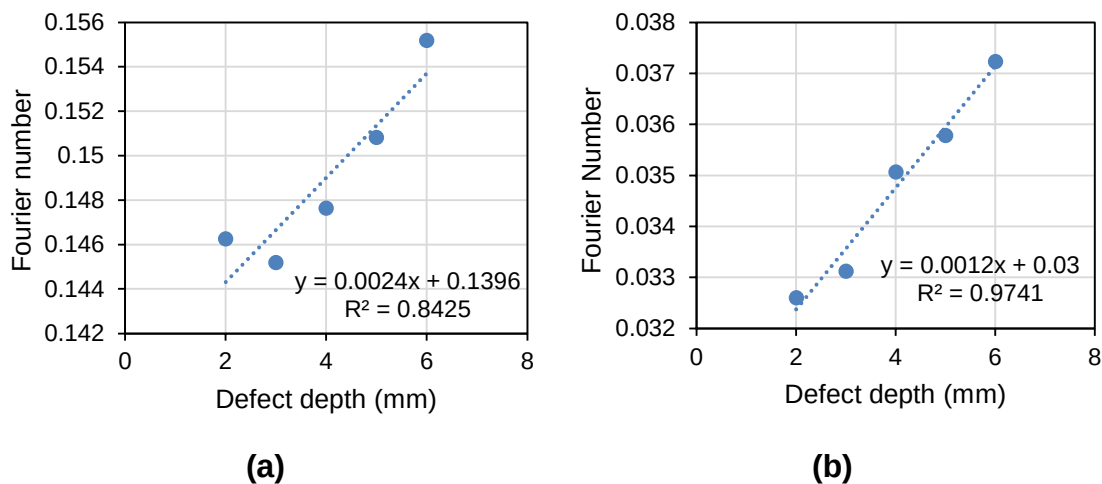
With the closeness of the FEM and laboratory experiments established in Section 4.4.2, the procedure outlined in Figure 4-6 was first applied to the FEM model.

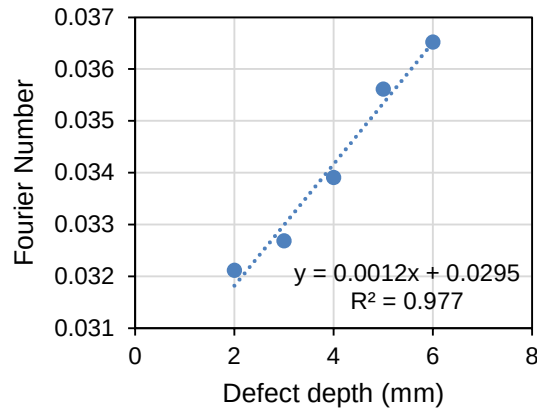
Additionally, the convention used to indicate the depth of the defect was modified. Previously, depth was measured from the rear side of the specimen due to plugs on the front side of the physical sample hindering reflection mode measurements. Now, all depth measurements are taken from the front side of the sample i.e., the side exposed to flash heating during through-transmission measurements. As a result, depths of 1 mm, 3 mm, and 5 mm (previously measured from the rear side) now correspond to 6 mm, 4 mm, and 2 mm respectively, when measured from the front surface. Furthermore, the simulation was repeated with the 2 mm and 4 mm depths adjusted to 3 mm and 5 mm, respectively, to obtain additional data points and develop a more comprehensive understanding of the relationship between defect depth and the Fourier number. Figure 4-15 shows the defect depths and their corresponding Fourier numbers calculated using Equation (4-8) for all the three different defect types.

Each defect type exhibits a positive linear correlation between its depth and the Fourier number. Since the characteristic length defined here as the defect diameter remains constant, the observed increase in the Fourier number with depth is governed entirely by the interaction between effective thermal diffusivity α and half-rise time $t_{1/2}$. From a physics perspective, this implies that for deeper defects, the heat has more time to diffuse across the defect region before the thermal response is detected at the rear surface. A higher Fourier number therefore reflects a more developed thermal diffusion process, indicating that the thermal wave has travelled a longer path and interacted more extensively with the sound material before reaching the airgap. This behaviour highlights the potential depth-sensitive nature of the thermal response in transmission mode, where deeper defects lead to an increased diffusion, possibly due to the thermal disparity between the sound and defect regions. The linear equation for each plot was obtained using the in-built linear trendline function available in Microsoft Excel. The R^2 value indicates that using a linear equation is sufficient to describe the relationship between the depth and Fourier number. While a polynomial regression mode using a higher order polynomial can be used e.g. a polynomial of order $n=2$, it results in an R^2 value of 1 which might indicate a stronger fit but could lead to over fitting. It must be noted that further work is required to develop

a deeper understanding of this relationship using different material types, material thicknesses, defect depths and shapes in order to standardise the regression model. However, for the purpose of this study adopting linear regression has shown to be sufficient for depth estimation.

Figure 4-15 also shows that the larger defects i.e., the 16 mm diameter circular and 16 mm length square defects exhibit a stronger correlation between depth and Fourier number compared to the 8 mm circular defect. This observation aligns with our current understanding of defect behaviour, where smaller defects are more difficult to characterise due to their lower thermal contrast relative to the surrounding sound material. Moreover, from a practical standpoint, the weaker correlation between the Fourier number and the 8 mm defect depth can also be attributed to the lower SNR in this region, as well as the camera’s minimum resolvable temperature difference. Enhancing these two factors could potentially improve the correlation and thus increase the accuracy of defect depth estimation.



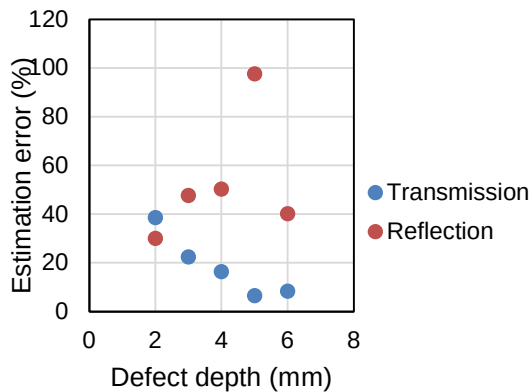


(c)

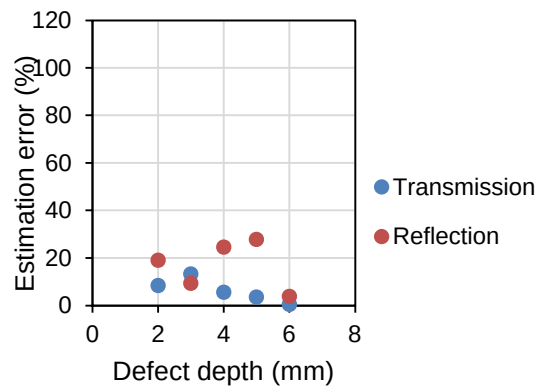
Figure 4-15 Defect depths with their corresponding Fourier number for a) 8mm circle b) 16mm circle and c) 16mm square defects

To further demonstrate the strength of the newly developed method's strength in quantifying defect depth, Figure 4-16 shows the defect depth estimation error for the reflection and transmission modes. For the reflection mode the Log Second Derivative method (LSD) first proposed by Shepard et al. [160] was used for the depth calculation. Knowing the thermal diffusivity of a material, the depth of the defect can be calculated using:

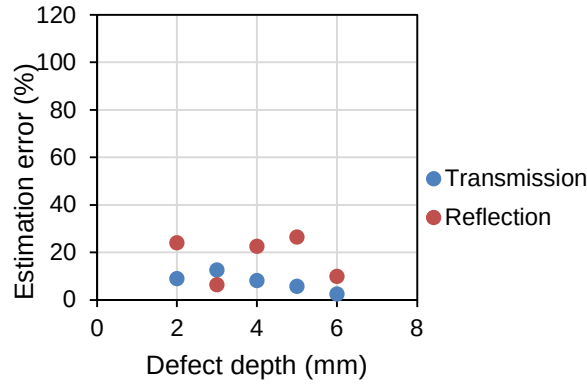
$$L = \sqrt{t_{LSD} \cdot \pi \cdot \alpha} \quad (4-9)$$



a)



b)



(c)

Figure 4-16 Defect depth estimation error using the reflection and transmission modes for a) 8mm circle b) 16mm circle and c) 16mm square

where t_{LSD} is the peak time of the second derivative and α is the thermal diffusivity of the sound material. For every defect type the proposed depth quantification technique exhibits a greater estimation accuracy to the established LSD method (an average error of 10.75% across all defect sizes and depths compared to LSD's 29.3%) especially at depths closer to the back surface. This is line with our current understanding of deeper sub-surface defects which are detected more clearly in the through-transmission configuration. Moreover, the average estimation error of the 8mm defect ($\approx 18.48\%$) is much higher than the 16mm defect ($\approx 6.26\%$), once again aligning with our current understanding of the effect of lateral defect size on the thermal response. It is important to note however, that the LSD method used here is a basic one computed in MATLAB. Industrial systems that implement LSD based on TSR utilise patent proprietary technology that has been optimised specifically for performance with other components with the system. Therefore, the performance of our computed TSR does not represent the performance that actual industrial systems would exhibit.

4.4.3.2 Laboratory experiments (Steel sample)

Following the FEM model, the same procedure shown in Figure 4-6 was applied to the physical sample. Unlike the FEM study, only 2 mm, 4 mm, and 6 mm depths were used due to physical limitations preventing inclusion of 3 mm and 5 mm on the same sample. Figure 4-17 illustrates the relationship between Fourier number and defect depth. Except for the 16 mm circular defect, the 6 mm depths show

weaker linearity, possibly due to factors such as lower signal-to-noise ratio, non-uniform heating, material inhomogeneity, heat interference from surface plugs, and manufacturing uncertainties. Still, the R^2 values indicate a reasonably strong positive correlation across all defect types, supporting the feasibility of depth estimation via a linear model.

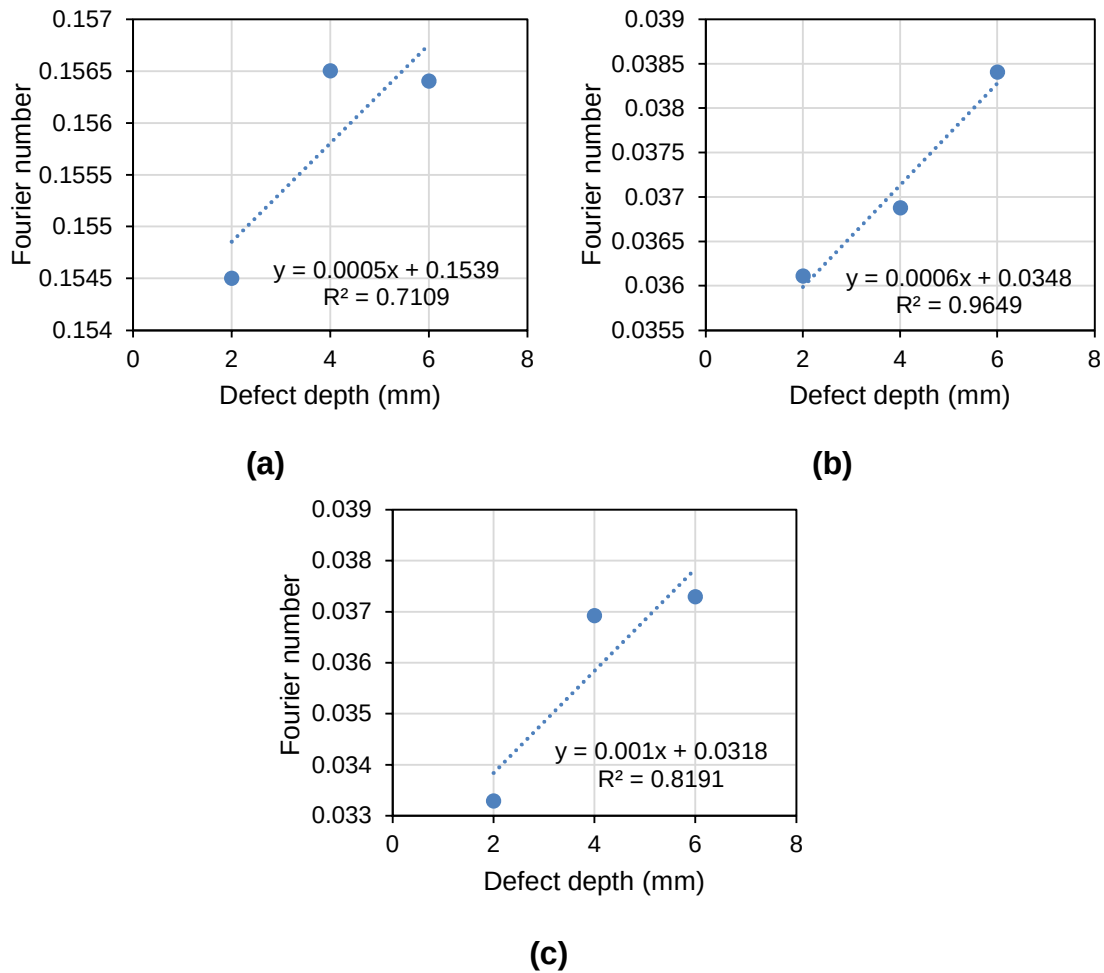


Figure 4-17 Defect depths with their corresponding Fourier number for a) 8mm circle b) 16mm circle and c) 16mm square defects for the laboratory experiments

Figure 4-18 presents the estimation errors. Reflection mode could not be evaluated experimentally due to front-surface plugs. Future work may involve more precise machining or symmetrical sample designs to enable dual-side measurements. Notably, the 16 mm circular defect showed the least average estimation error ($\approx 7.67\%$), aligning with its strong linear fit. Additionally, the experimental error trends closely match FEM results, reinforcing FEM's value for analysing complex scenarios beyond practical experimental reach. It is important

to note that the 16mm square defect's error is double the 16mm circle's indicating that manufacturing uncertainties as well as geometrical features also have a role in determining the measurement accuracy and this sensitivity will be the subject of a future study.

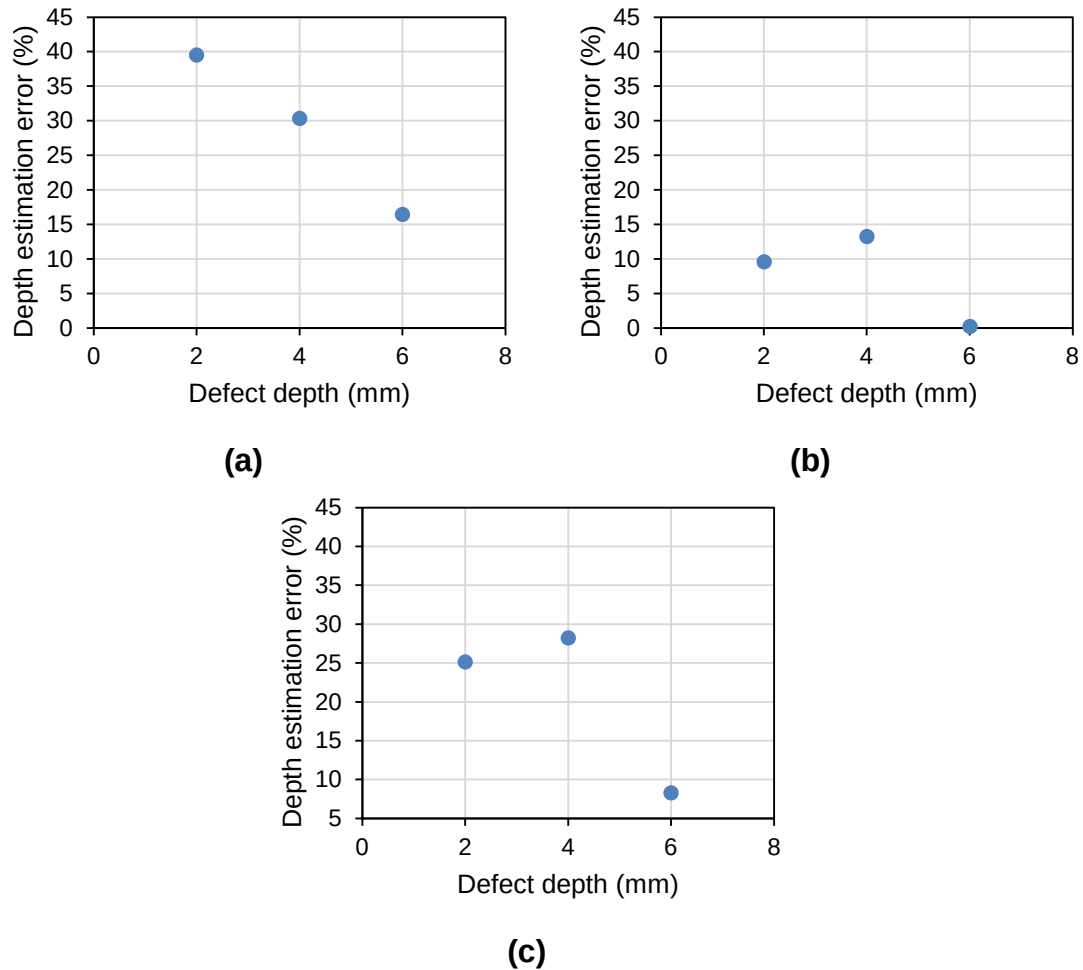


Figure 4-18 Defect depth estimation error for the laboratory experiments using the transmission modes for a) 8mm circle b) 16mm circle and c) 16mm square

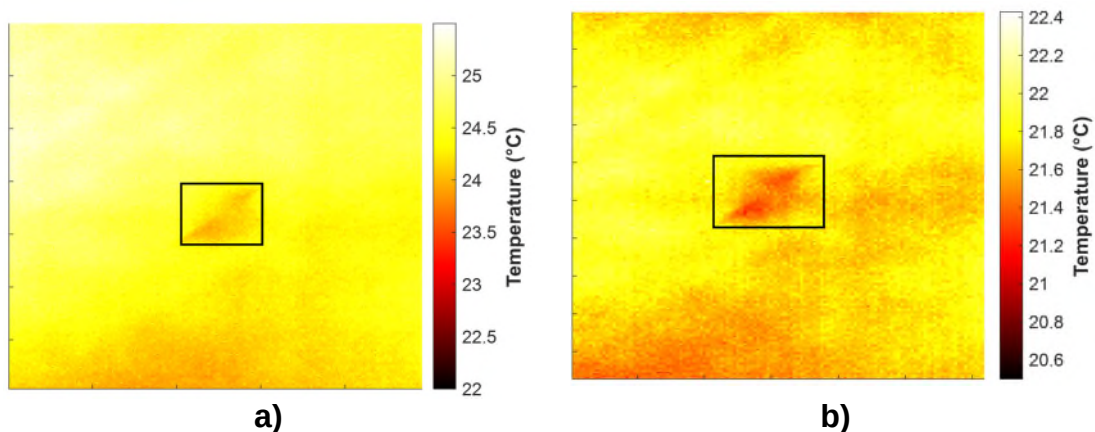
4.4.4 Impact damage estimation for CFRP samples

Figure 4-19 displays representative raw thermograms of the CFRP samples impacted at varying energy levels, captured using both longwave and mid-wave infrared cameras in the TB configuration. The thermograms were taken at 3.76 seconds or 188 frames after flash. As shown in Figure 4-10, black rectangles denote the defect regions. Both cameras successfully detect defects resulting from all impact levels. However, the mid-wave camera demonstrates slightly

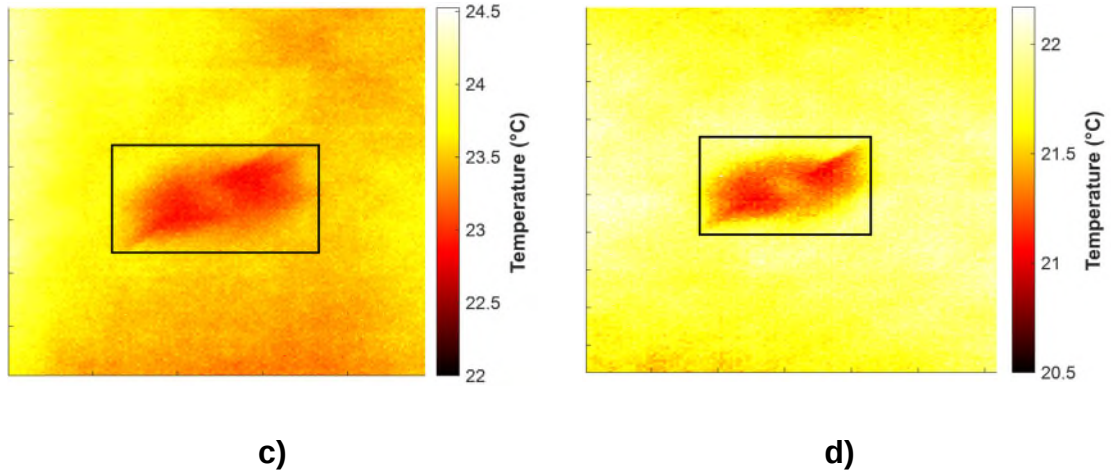
superior spatial resolution, providing clearer defect characterisation compared to the longwave camera. As mentioned previously, the resolution of defects is not the main objective of this study which is why no image enhancement algorithms were applied to improve visual clarity. The focus is on the accurate estimation of effective thermal diffusivity, for which the raw thermograms provide sufficient temporal information. It is observed that the variation between repeats is less for the longwave camera compared to the mid-wave camera. This is consistent with the theory of peak spectral emission, which establishes a direct relationship between temperature and the wavelength at which peak emission occurs. As the temperature increase is relatively small, the long-wave camera captures the backwall's temporal behaviour with greater precision than the mid-wave camera as indicated by the reduced variation in the boxplots shown in Figure 4-20 and Figure 4-21. The box plots in Figure 4-20 and Figure 4-21 show the thermal diffusivity and input energies for both cameras respectively in the TB configuration.

It is observed that the variation between repeats is less for the longwave camera compared to the mid-wave camera. This is consistent with the theory of peak spectral emission, which establishes a direct relationship between temperature and the wavelength at which peak emission occurs. As the temperature increase is relatively small, the long-wave camera captures the backwall's temporal behaviour with greater precision than the mid-wave camera as indicated by the reduced variation in the boxplots shown in Figure 4-20 and Figure 4-21.

4J



8J



12J

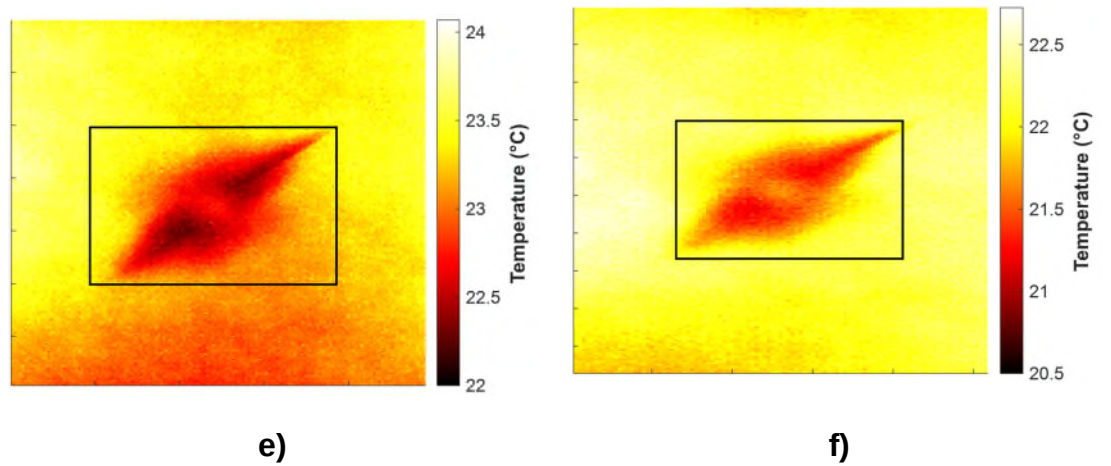
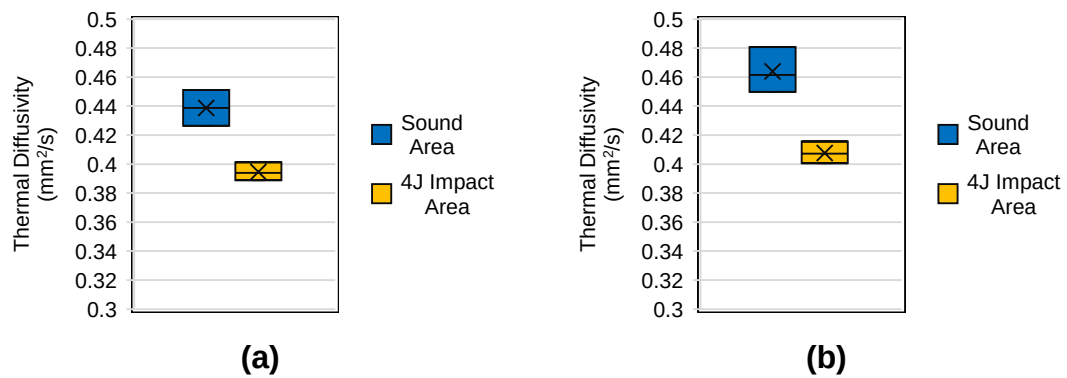
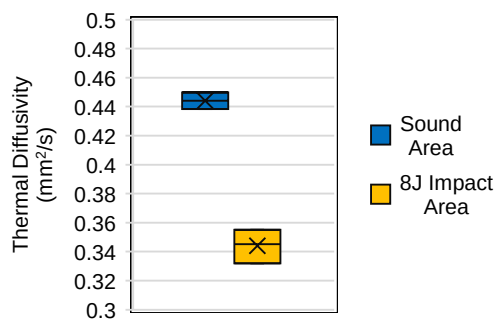
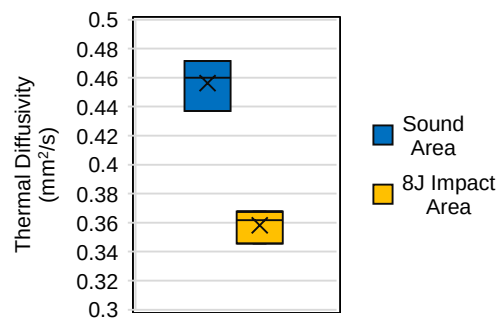


Figure 4-19 Raw thermograms for the impact samples at 4J, 8J and 12J using the longwave (a, c, e) and mid-wave (b, d, f) cameras in the TB configurations (image taken 3.76 seconds or 188 frames after flash)

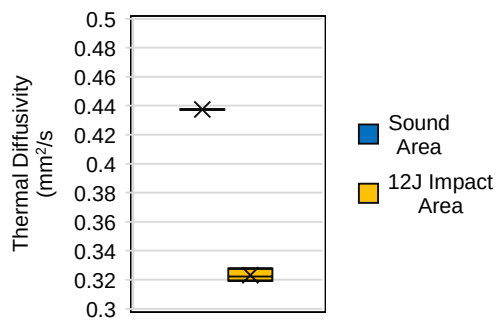




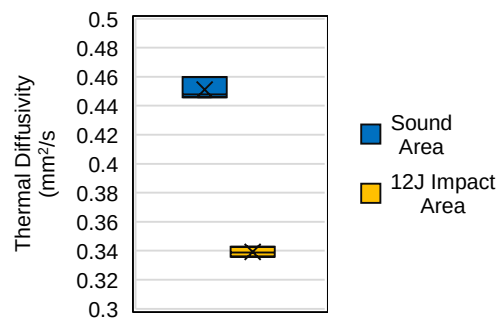
(c)



(d)

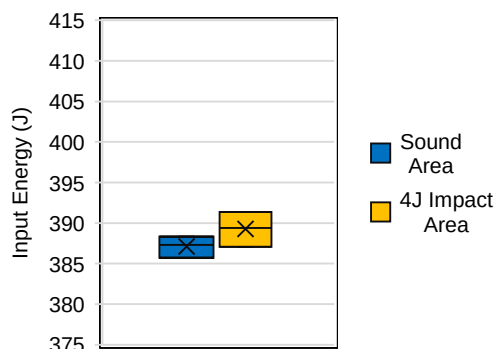


(e)

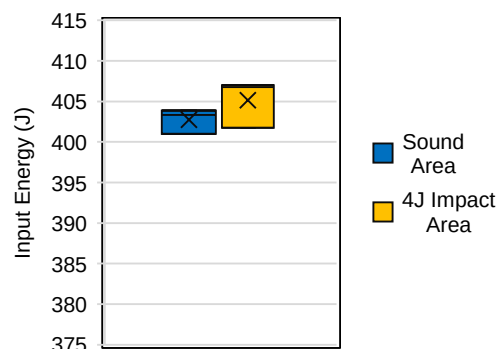


(f)

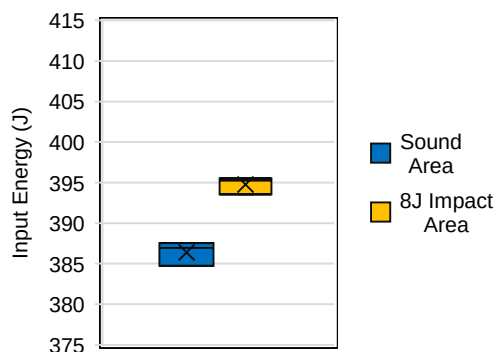
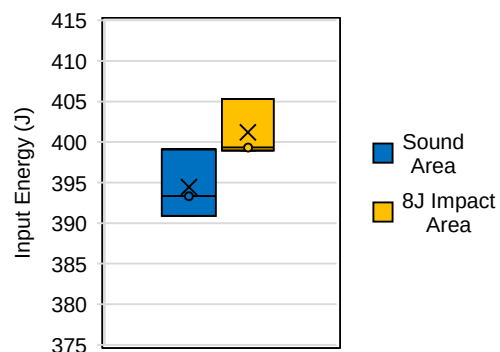
Figure 4-20 Thermal diffusivity estimation in TB configuration using the long-wave (a, c, e) and mid-wave (b, d, f) cameras



(a)



(b)



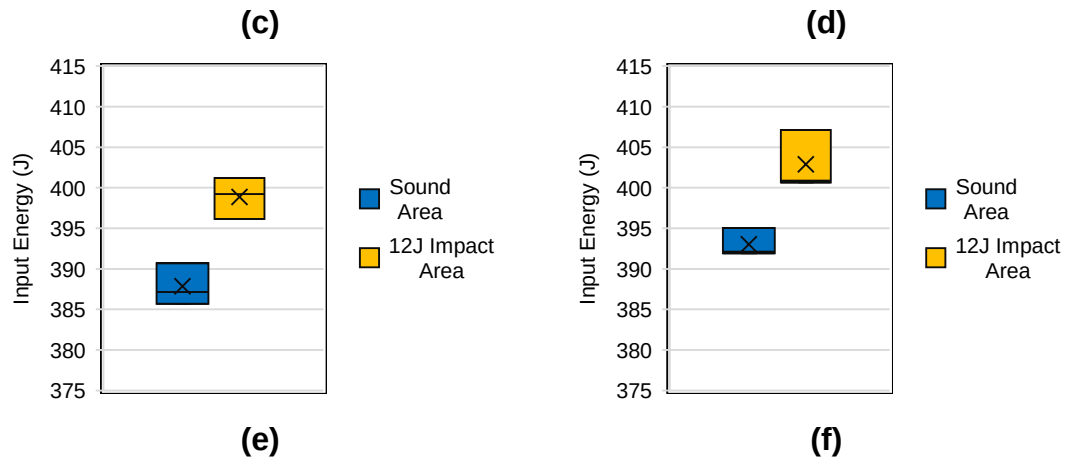


Figure 4-21 Input energy estimation in TB configuration using the long-wave (a, c, e) and mid-wave (b, d, f) cameras

It can be inferred from Figure 4-20 that the effective thermal diffusivity decreases as the impact energy increases. This is in line with the understanding that a higher impact energy would cause a larger damage (in this case a delamination) thereby reducing the rate at which heat can travel through the thickness of the sample. A close examination of the effective thermal diffusivity values reveals that the change is more pronounced when the impact energy increases from 4J to 8J than from 8J to 12J. This trend is consistent across both the long-wave and mid-wave infrared camera data, suggesting that the extent of the damage is greater in the CFRP samples when the impact energy is increased from 4J to 8J compared to 8J to 12J. While the increase in impact energy is uniform, the corresponding increase in damage is not, indicating a nonlinear relationship between impact energy and thermal damage severity. The results have not been shown for the TF configuration; however the relative precision of the estimated values is once again found to be greater in the longwave camera.

Since the depth of the damage in the CFRP samples is unknown a relationship between the Fourier number and impact energy is established instead of the depth. Figure 4-22 shows the sensitivity of the Fourier number to the impact energy. Analysis of the plot slopes indicates that Fourier number calculations based on temperature data from the longwave camera exhibit greater sensitivity compared to the mid-wave camera, with a 200% increase in the TF configuration and a 50% increase in the TB configuration. This sensitivity is translated into more

accurate assessments of impact energy in Figure 4-23. In terms of correlation, all plots exhibit a strong negative correlation which is attributed to the fact that a larger defect would result in a lower effective thermal diffusivity and a larger value for the half-rise time as the backwall temperature increases at a slower rate. Based on the current analysis it could be concluded that the longwave camera is better suited for this type of analysis. The use of the longwave camera for impact energy assessment is further strengthened in Figure 4-23 where the TF configuration using the longwave camera produces the most accurate estimates of the impact energy. Moreover, the accuracy increases with increasing impact energy for the longwave camera as opposed to the mid-wave camera where no such trend between impact energy and estimation error is observed. Finally, as demonstrated using the steel sample, it is important to evaluate how accurately the NLSF algorithm captures the backwall temperature rise. To this end, residual analysis will be performed for both cameras in the TF and TB configurations.

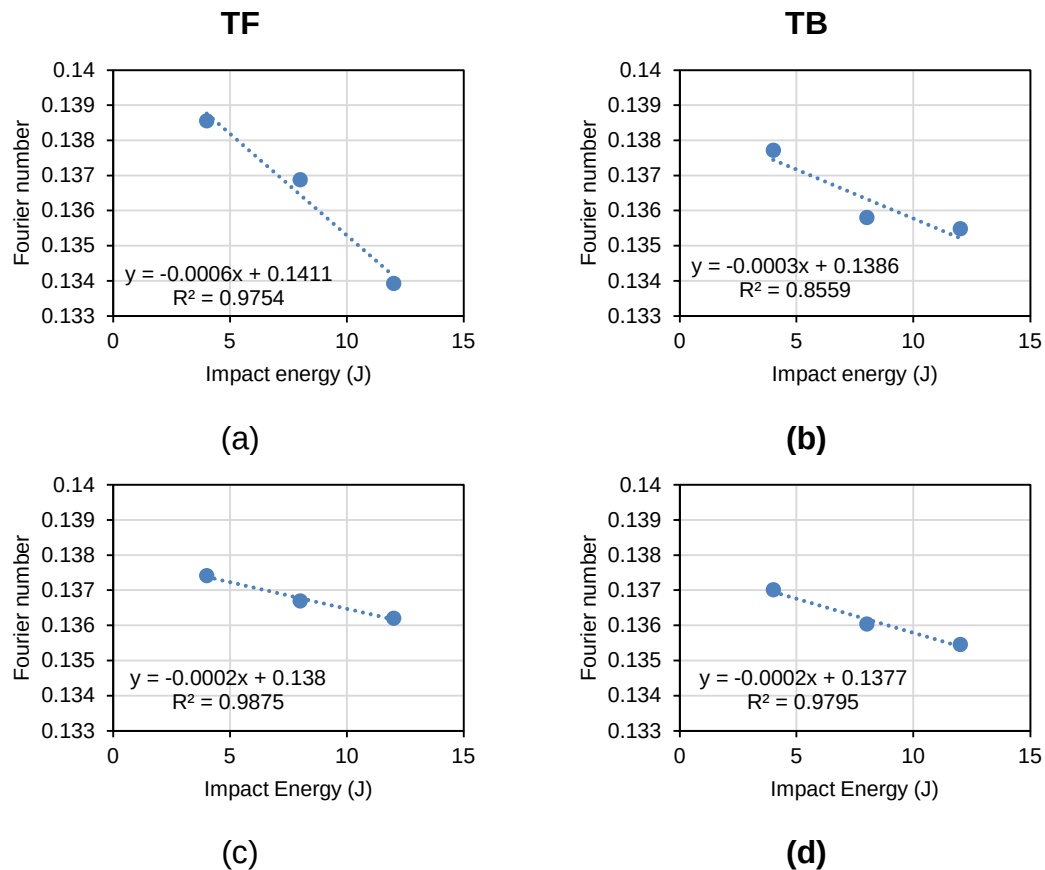


Figure 4-22 Fourier number sensitivity to impact energy using the longwave camera (a & b) and mid-wave camera (c & d) in both the TF and TB configurations

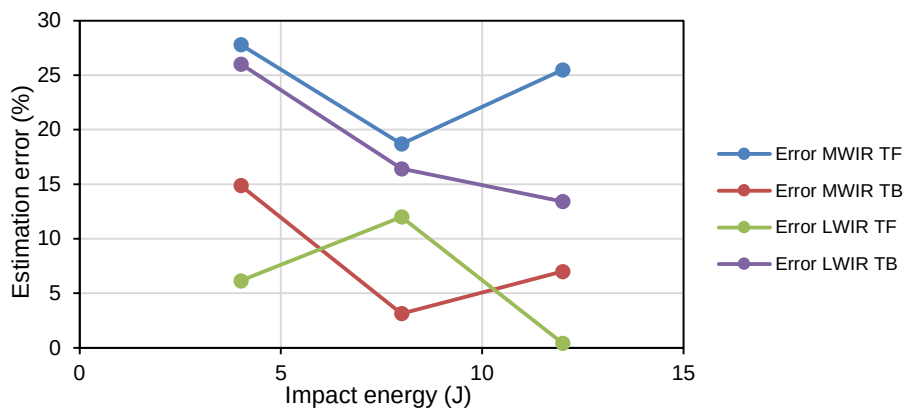


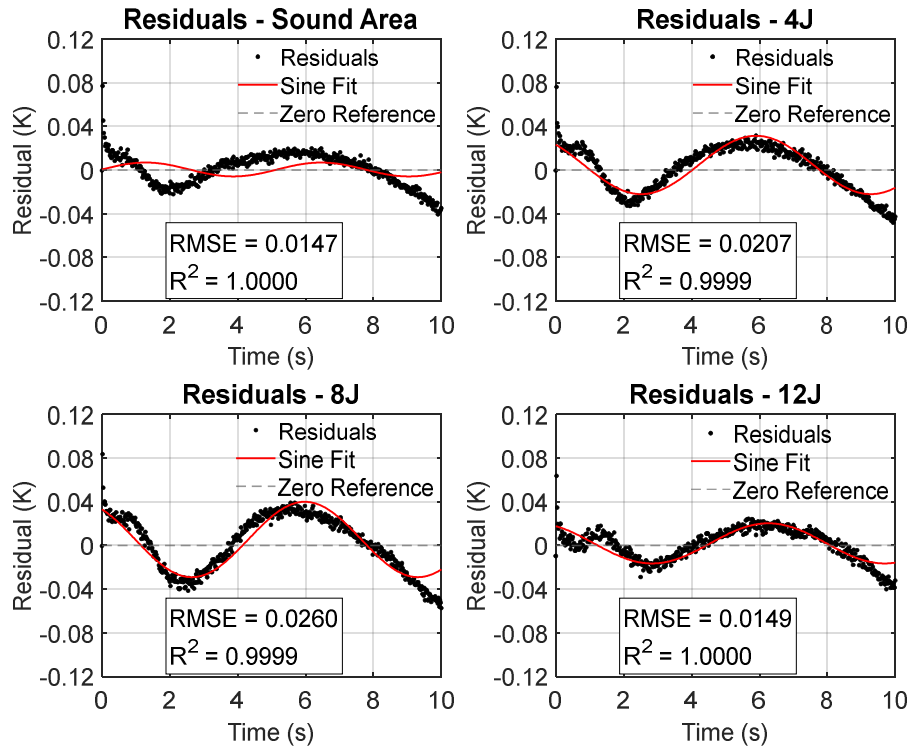
Figure 4-23 Impact energy estimation error for both TF and TB configurations using the longwave and mid-wave cameras

4.4.4.1 Mid-wave camera

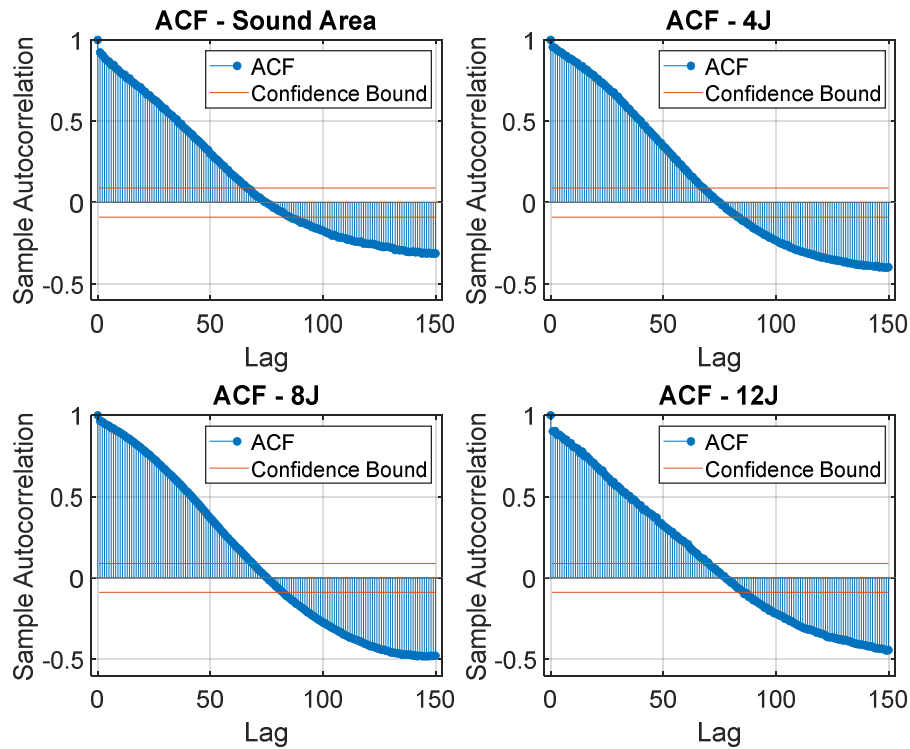
Figure 4-24 and Figure 4-25 show the residual plots for the TF and TB configurations respectively and their corresponding autocorrelation function plots (ACF). The ACF quantifies the correlation of a signal with itself over different time lags, providing a measure of how residuals are temporally related and allowing detection of systematic patterns not captured by the model. It is evident from both Figure 4-24 and Figure 4-25 that while statistically the NLSF algorithm captures the backwall temperature with reasonable levels of accuracy (as indicated by the R^2 and RMSE values), a visual inspection of the residual plot reveals a sinusoidal pattern indicative of a systematic error.

To explore this further, a sinusoidal function was fitted to the residuals, and autocorrelation analysis was performed. The ACF plots were computed up to 150 lags, corresponding to approximately 3 seconds of the signal, which covers the most dynamic part of the thermal response i.e., the temperature rise. These plots revealed a gradual, smooth decay across increasing lags, with autocorrelation coefficients remaining significantly above the 95% confidence bounds for a considerable portion of this range. This behaviour suggests that the residuals exhibit weak but persistent temporal structure, rather than behaving as random

noise. The presence of such correlated residuals, alongside the fitted sinusoidal trend, points to minor systematic effects in the thermal signal.

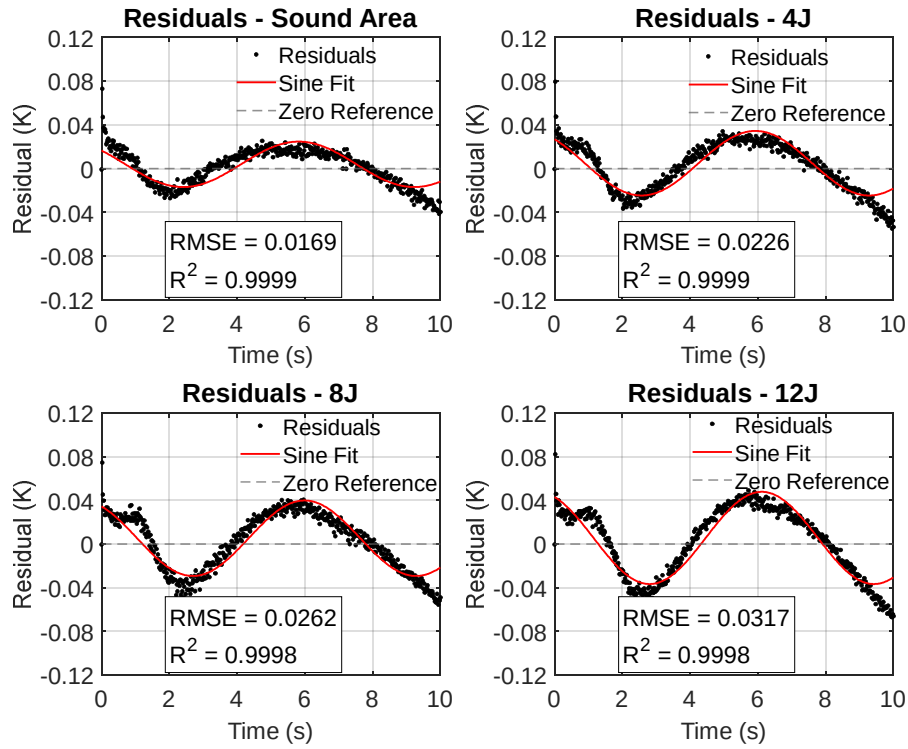


(a)

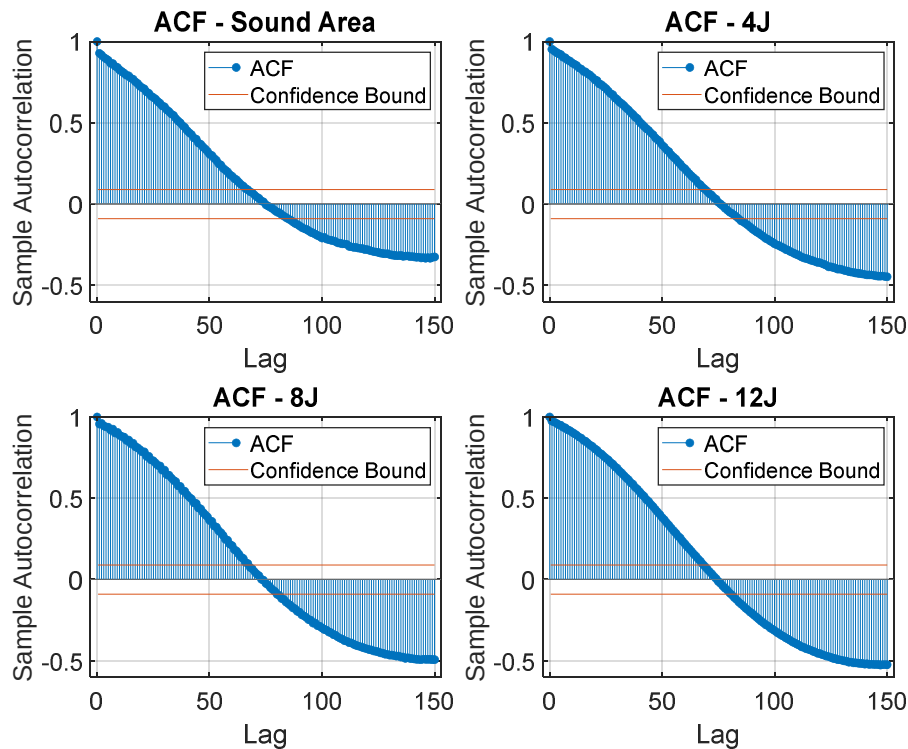


(b)

Figure 4-24 a) Residual analysis of the TF configuration and its b) autocorrelation analysis for the mid-wave camera



(a)



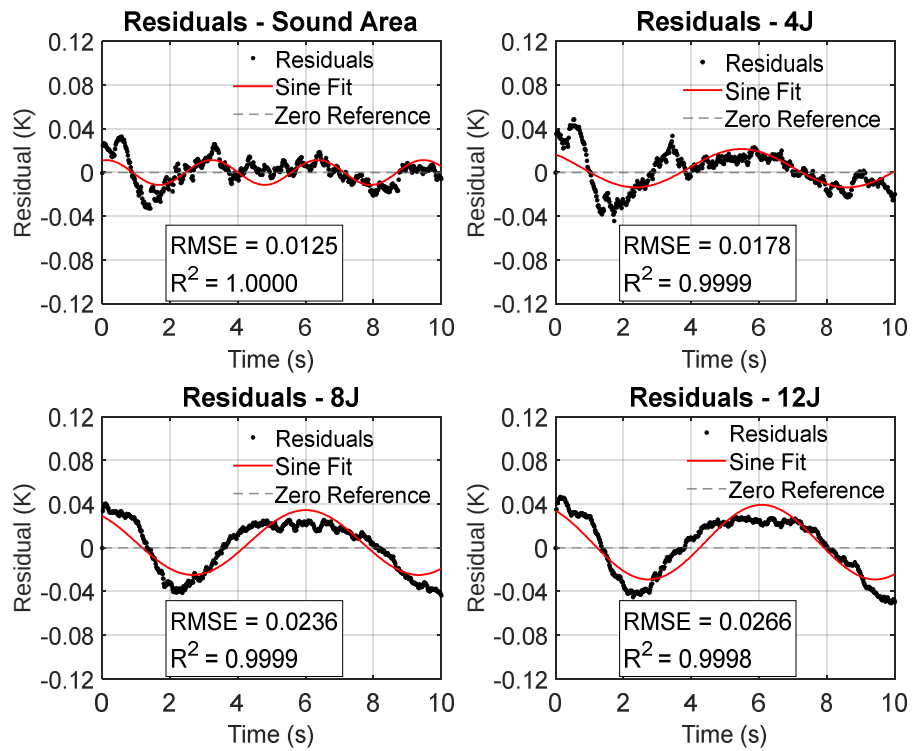
(b)

Figure 4-25 a) Residual analysis of the TB configuration and its b) autocorrelation analysis for the mid-wave camera

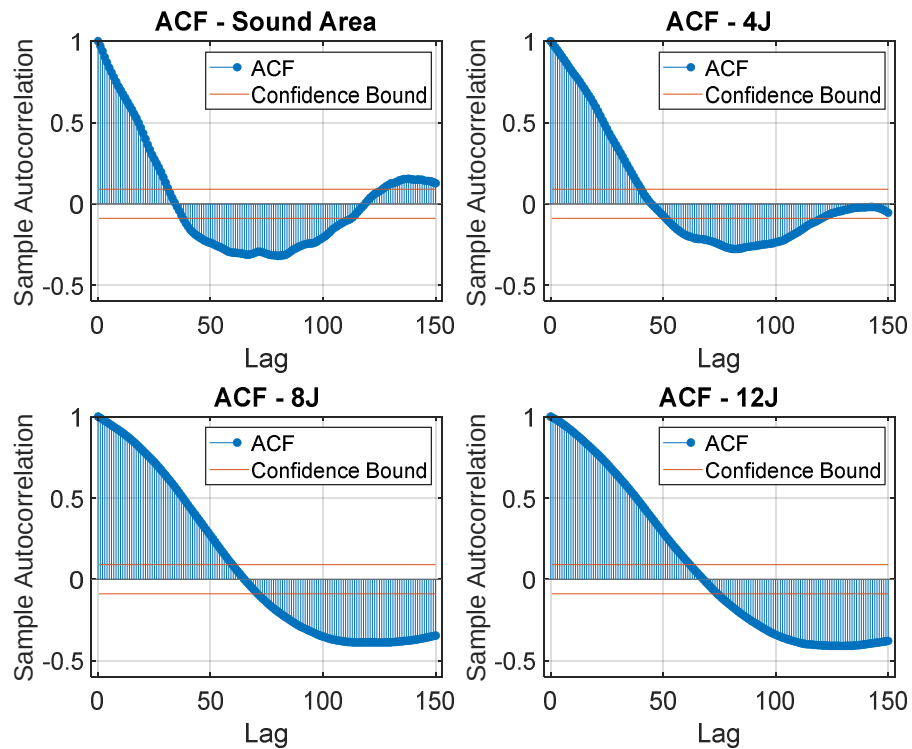
These could arise from boundary interactions, IR sensor dynamics, or from the simplifications in the 1-D heat conduction model used. Despite these observations, the overall residuals remain small, and the model fits the measured data very well. This suggests the model remains practical and reliable for interpreting transient thermal behaviour. Future work could consider refining the model to include multidimensional effects or correction terms to better reflect the actual thermal behaviour.

4.4.4.2 Longwave Camera

Figure 4-26 and Figure 4-27 show the residual and ACF plots for the long-wave camera in the TF and TB configurations, respectively. Although a small sinusoidal pattern is present, it is much weaker compared to their mid-wave counterparts. Furthermore, analysis of the ACF initially shows a gradual decay, indicating some short-term correlation, but quickly falls within the confidence bounds, suggesting limited longer-term autocorrelation, particularly with the Sound and 4J data in the TF configuration. This also explains why the TF configuration produced the most accurate estimates for impact energy, as shown in Figure 4-23. Analysing the residual and ACF plots further strengthen the case for using the longwave camera for through-transmission analysis.

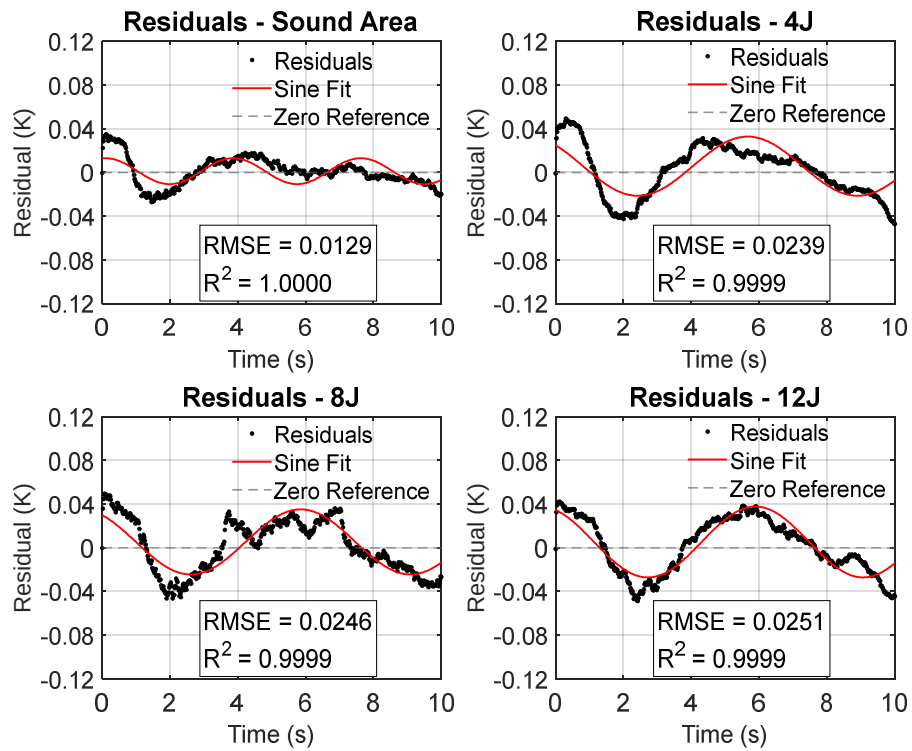


(a)

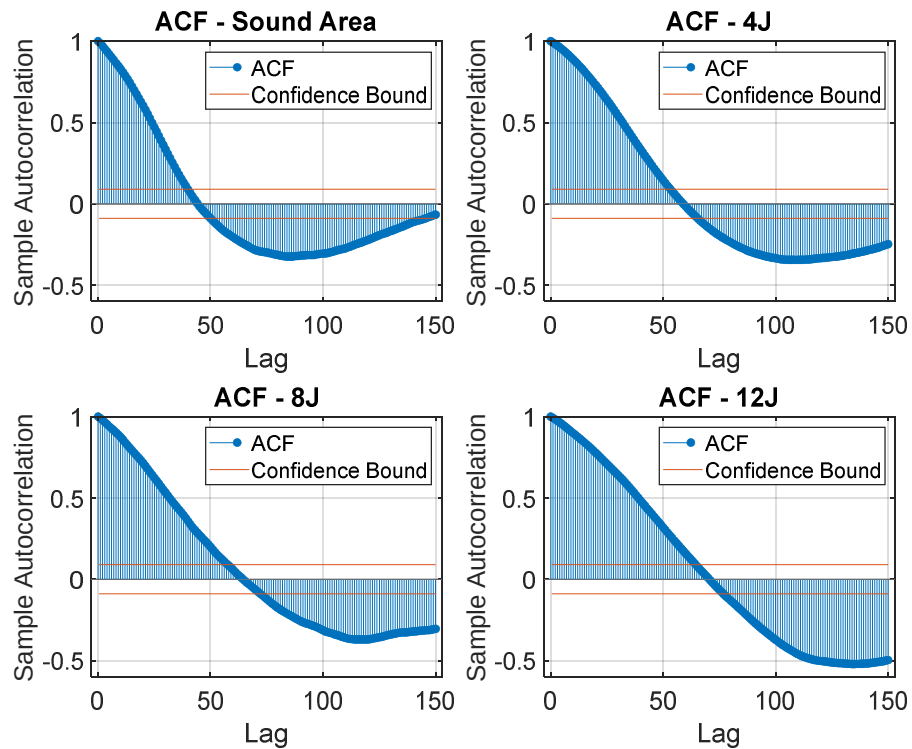


(b)

Figure 4-26 a) Residual analysis of the TF configuration and its b) autocorrelation analysis for the longwave camera



(a)



(b)

Figure 4-27 a) Residual analysis of the TB configuration and its b) autocorrelation analysis for the longwave camera

4.5 Summary and Conclusion

This study performs a detailed analysis of the thermal response of a sample with embedded defects subjected to pulsed heating. Analysis is conducted in both simulation and laboratory environment. The key takeaways from this work are listed below

4.5.1 Summary

- Finite element analysis was conducted where a steel sample was created with sub-surface air gaps and subjected to pulsed heating with the temperature information being captured in both the reflection and transmission modes. Due to the addition of plugs in the physical samples, the rear side of the sample in both the FEM and physical experiments was the one exposed to flash heating and data capture in the reflection mode (See section 4.3.2).
- A sample with embedded air gaps at known defects was manufactured to address the lack of calibration samples for through-transmission pulsed thermography (See section 4.3.3).
- A proposed solution is presented to quantify defect depth by establishing a relationship with the Fourier number. This approach is further extended to quantify impact damage, using the same relationship, but applied between impact damage and the Fourier number.

4.5.2 Conclusions

- For through-transmission pulsed thermography, the depth quantification has been a challenge due to the distance travelled by the thermal wave being the same for the defect and defect free regions. Moreover, a calibration sample with actual sub-surface air gap defects (an equivalent to flat bottom holes for the reflection mode) did not exist further complicating the problem (See section 4.1.2).
- Performing a dual-mode analysis by analysing the first derivative curves for both the reflection and transmission mode revealed that the peaks of the transmission mode occurred at similar times regardless of defect depth

whereas the reflection mode peaks shifted closer to their through-transmission counterparts as the defect depth from the surface increased. This indicated that an approximate location of the defect depth can be estimated by observing both the first derivative peaks however it still cannot be used to quantify the defect depth (See section 4.4.1.1 & 4.4.2.1).

- A potential solution to quantify defect depth is developed by establishing a relationship between the Fourier number and defect depth. The estimation error is compared with the reflection mode using basic TSR/LSD method in the FEM. The results from both FEM and laboratory experiments indicate that the accuracy of the proposed solution is greater at defects closer to the backwall (See section 4.4.3.2).
- The newly proposed method is extended to quantify impact damage in CFRP samples. The results show that the TF configuration using the longwave IR camera is best suited for this type of analysis. Moreover, the ACF plots reveal minor systematic deviations which would need to be corrected for in order to develop a more representative mathematical model to describe the backwall temporal behaviour. (See section 4.4.4)

While this study offers a promising solution for depth quantification in through-transmission pulsed thermography, it has several limitations. First, the laboratory experiments lack a comparative analysis with reflection mode techniques such as Pulsed Phase Thermography, beyond TSR, to fully assess accuracy. Second, all defects used a fixed height of 1 mm, which is why future work should explore varying defect heights, depths, and geometries. Third, only two material types were investigated; studies on materials with different thermal diffusivities or heterogeneous properties are needed. Finally, the ACF plots have revealed systematic deviations resulting from using the current 1-D model to describe the backwall temperature evolution. Future work would involve correcting the current model to reduce or even potentially eliminate these deviations. Despite these limitations, this study's primary contribution is its clear methodology for evaluating depth quantification in through-transmission mode. The results lay the groundwork for advancing both analytical and experimental approaches in defect depth characterisation.

Author Contributions: Ali, Z, conceptualization, methodology, writing—original draft preparation; Addepalli, S conceptualization, review and editing, funding acquisition; Zhao, Y review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

5 Critical discussion of results and their impact

This section presents the major findings of this thesis, tracing the research progression from the initial systematic review through to the final study that established the depth quantification methodology. Each of Chapters 2 to 4 is first discussed individually, followed by a broader discussion on how the findings collectively contribute to industrial practice. Finally, this section highlights how each chapter, while published as a standalone study, contributes to the overarching objective of this thesis: the development of a robust through-transmission thermography technique for material characterisation.

5.1 Deliberation of the systematic literature review

The primary motivation for conducting the systematic literature was to perform a comprehensive analysis of the state-of-the-art in through transmission thermography with a focus on its technique development. The idea was to generate a renewed interest within the thermography community for the technique development of the transmission mode. Through this review, the lack of theoretical models in pulsed thermography and the outdated practices in thermal diffusivity estimation were identified. In other words, the systematic review was crucial in shaping the research direction of this thesis. In contrast to many general reviews, which often identify research gaps retrospectively and are prone to bias, a systematic review follows a transparent, predefined methodology, with the motivation and research aims established from the outset. It also justifies the analytical approaches used, ensuring they are directly aligned with the review's primary objectives.

Moreover, the transparent methodology also allows the review to be easily updated in the future. For example, when the search was conducted on the 1st July 2024, a total of 379 articles were identified. Since the exact search strings that were used have been listed, they can be used to repeat the search. As of the 26th of April 2025, the 379 articles that were initially identified have now risen to 410. Using the same inclusion and exclusion criteria outlined in Table 2-3 an additional 9 articles including the systematic literature review (Chapter 2) and the

methodology for effective thermal diffusivity estimation (Chapter 3) can be added to the collection bringing the total number of papers from 82 to 91 [13,14,205–211]. However, the major gap remains the same. No theoretical or experimental work is present in the current literature that provides a methodology or framework to quantify the defect depth in through transmission pulsed thermography. Currently, most research on thermal diffusivity estimation focuses on evaluating in-plane thermal diffusivity, with comparatively limited attention given to through-thickness (in-depth) measurements. Furthermore, since the determination of in-plane thermal diffusivity is primarily conducted in reflection mode, many articles published after the systematic review date were excluded, resulting in only nine articles being included in this review, despite a 31 article increase in the total number of publications.

In terms of technique development and the current state-of-the-art, the conclusions presented in Chapter 2 will have to be slightly amended to include the use of through transmission thermography in developing mid-infrared bandpass filters for carbon dioxide sensing [209], as well the thermal diffusivity estimate of fluids [206]. Although the temperature sensing device used in [206] is not an infrared radiometer, the through-transmission technique is still fundamentally applied, and the use of an infrared radiometer for temperature measurements remains entirely feasible. One of the knowledge gaps identified in the review was the lack of a transparent methodology for thermal diffusivity estimation using through-transmission pulsed thermography, which has since been addressed (see Chapter 3), albeit with certain limitations (see Section 5.2).

5.2 Performance and reliability of the thermal diffusivity estimation method

The conclusion section of the systematic review presented several recommendations to address some of the knowledge gaps that were identified. The follow up study presented in Chapter 3 is a natural progression built on the conclusions presented by its predecessor i.e., the systematic review. Here a full factorial DoE was developed to analyse the effect of two different parameters, flash energy and sample thickness on estimating the thermal diffusivity.

Moreover, it sought to update the current practice of thermal diffusivity measurement in pulsed thermography which still uses Parker's half-rise equation. Although the current method is robust and has been implemented in commercial systems, it relies on certain assumptions that require specialised equipment to support them. For instance, the method assumes that the data capture occurs right after the flash event which is only possible if a system is in place to synchronise the flash with the data acquisition. Moreover, it does not consider heat losses that might affect the value of the thermal diffusivity. While commercial systems use temperature-controlled chambers and multiple calibrations to circumvent this issue, they are often expensive to use, thereby reducing the feasibility of the method.

To address the above-mentioned challenges, an updated methodology for thermal diffusivity measurement is developed using the NLSF algorithm. The advantage of using the NLSF method over the classical Parker's method is that it uses the entirety of Parker's equation for the backwall instead of just the half-rise time, thus giving a better representation of the materials backwall temporal behaviour. However, to prove that the proposed technique is accurate, it needs to be benchmarked against known values of the parameters it is trying to estimate. Also, the new method needs to be compared with an existing method to demonstrate its effectiveness for thermal diffusivity measurement, which in this case was the Parker's half-rise method. For this reason, the method was initially implemented within a finite element modelling (FEM) environment, where input parameters were directly controlled by the researcher. Following the theoretical validation of the NLSF approach, experimental testing was conducted. A comparison between FEM simulations and experimental results demonstrated that the proposed method yields higher precision in estimating thermal diffusivity, particularly at lower specimen thicknesses and elevated flash energy levels, compared to conventional techniques. The findings clearly demonstrate that the NLSF algorithm yields more accurate and reliable thermal diffusivity values than the traditional Parker method. This superiority justifies its exclusive use in Chapter 4 for enhanced modelling fidelity.

While the validity of the NLSF method was established here, it was not without its limitations. Firstly, thermal diffusivity is a quantity that can also be measured in the reflection mode. Due to the volume of the results presented in this study, this was planned for a future study. Moreover, this did not align with the scope of thesis which is why it was not included. However, existing research has already demonstrated the robustness of the transmission mode when it comes to material characterisation compared to the reflection mode [4,198]. While it can be argued that the previous study did not employ the NLSF method for a direct comparative analysis, the findings presented in Chapter 3 provide evidence that its conclusions would likely align with those established in this work.

Secondly, only a single specimen per thickness was analysed. For a more robust and statistically meaningful evaluation, future studies should include a minimum of three specimens for each thickness. This could possibly reduce some of the effect of thickness variations in thermal diffusivity estimation observed in Figure 3-15. Thirdly, as discussed in Chapter 4, the positioning of the sample when using an open flash system, such as the one employed in this study can significantly affect the energy distribution across the sample surface. The adjustment made in Chapter 4 to concentrate the heat emitted from the flash onto the centre of the sample was not applied in this case. The issue of uneven heating was only identified due to the positioning of defects across the sample, which was not a concern here, as data for non-defect samples was consistently captured from the same region. Ideally, the heat should have been concentrated at the centre of the sample, as this was the region from which the backwall temporal information was extracted. Moreover, since this study investigated the effect of input energy on the estimation of thermal diffusivity, this is an important factor that should have been considered. However, this does not detract from the study's conclusions, as it has already been established that higher energy levels lead to greater temperature increases, thereby enhancing the overall accuracy of thermal diffusivity estimation. Although the heat was not focused on the centre, it was consistently concentrated on the same spot across all runs, maintaining the validity of the conclusions. Concentrating the heat at the centre would only serve to further improve the accuracy of the thermal diffusivity estimates. Lastly, a major

factor for the disparity between the simulation and experiments was the peak spectral emission of the sample under observation. The simulation assumes that the peak spectral emission is equal across all wavelengths while physical experiments show that this is not the case. Since the camera used was a mid-wave camera (3–5 μm), the experiments should ideally be repeated with a long-wave infrared camera (7.5–15 μm). Incorporating these suggestions into the methodology outlined in Chapter 3 will enable a more comprehensive analysis of the proposed approach for thermal diffusivity estimation. Nevertheless, the proposed suggestions do not undermine the methodology, as they do not alter the way the results were analysed, only the inputs to the study would need to be modified.

5.3 Insights into depth quantification technique

With a validated FEM model of a defect-free sample, the next step involved modifying the model by introducing representative sub-surface defects in the form of air gaps at varying depths. This was to observe the effect of airgaps on estimating the effective thermal diffusivity. It is important to note that the term 'effective' is used here to describe the thermal diffusivity within the defect regions. The rationale behind this as explained by Maierhofer et al. [4] is that, where it states that the effective diffusivity is composed of a slower heat diffusion rate through the delamination layers as the thermal contact resistance is enhanced around the defects. Since it was already established in a previous study that the lateral defect size has a greater influence on the backwall temporal behaviour [142], this study focused primarily on varying different defect depths. While defects of different sizes were created, the analysis in terms of defect depth was done separately for each defect type. Defects were positioned near the front surface, mid-thickness, and close to the backwall to systematically observe the influence of depth on the backwall thermal response and to ensure coverage across the majority of the sample thickness (2mm, 4mm, and 6mm as measured from the front wall with a 1mm defect thickness). Moreover, since the superiority of the NLSF algorithm was established in Chapter 3, it was used exclusively for thermal diffusivity measurements and the subsequent depth quantification.

Running the simulation revealed an interesting insight in terms of the temperature rise on the backwall. Compared to the temporal behaviour of the sound area, all defect regions exhibited a temperature rise at a slower rate which is expected as air has a much lower thermal conductivity compared to steel. However observing the defect regions exclusively showed that while the effective thermal diffusivity reduced from 2mm to 4mm, it increased for the 6mm defect. This is a phenomenon that was not explored in the existing body of literature. Moreover, this phenomenon was observed across all defect types indicating that this behaviour is defect geometry independent. To further understand this phenomenon, the first derivative plots were constructed for the defect regions. It is important to highlight that this type of analysis was only made possible through the curve fitting capabilities of the NLSF algorithm. Without it, the generation of accurate first derivative curves, and consequently this level of detailed analysis, including the subsequent comparative analysis with the reflection mode, would not have been achievable. The first derivative plots in the transmission mode did not reveal any major insights except the fact that the first derivative peaks occur at similar times regardless of depth aligning with our current understanding of the depth quantification capabilities of the transmission mode.

To ensure that the backwall temporal distribution is accurate and without errors in the FEM, it was vital that this phenomenon was observed experimentally as well. A major challenge in experimentally validating this observation was designing a sample that contains subsurface airgaps, something that was not available in current literature. A plausible reason for the absence of calibration samples for the transmission mode, similar to flat-bottom holes used in reflection mode, may be the inherent difficulty of depth quantification in through-transmission, thereby reducing the incentive for researchers to develop such samples. Additionally, a major portion of pulsed thermographic research has been focused on composite materials such as CFRPs [212,213] and due to the nature of the manufacturing process of CFRPs, developing a sample with subsurface airgaps is extremely challenging. This limitation has prompted researchers to adopt alternative approaches in-line with the published literature. This included embedding Teflon inserts; materials with lower thermal conductivity

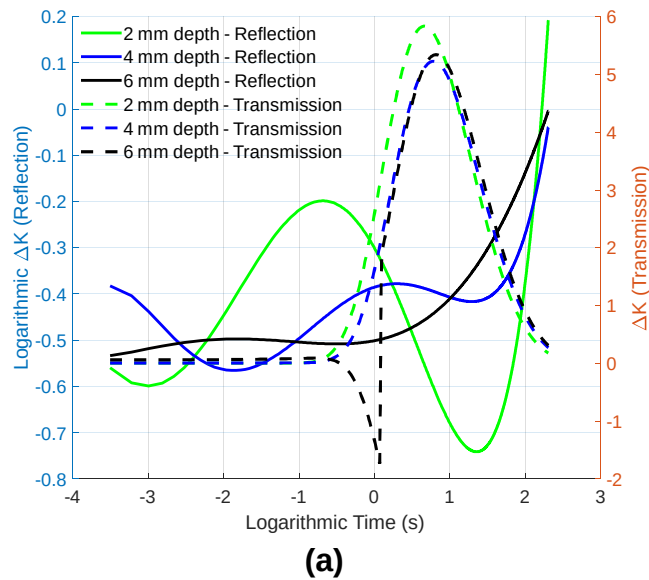
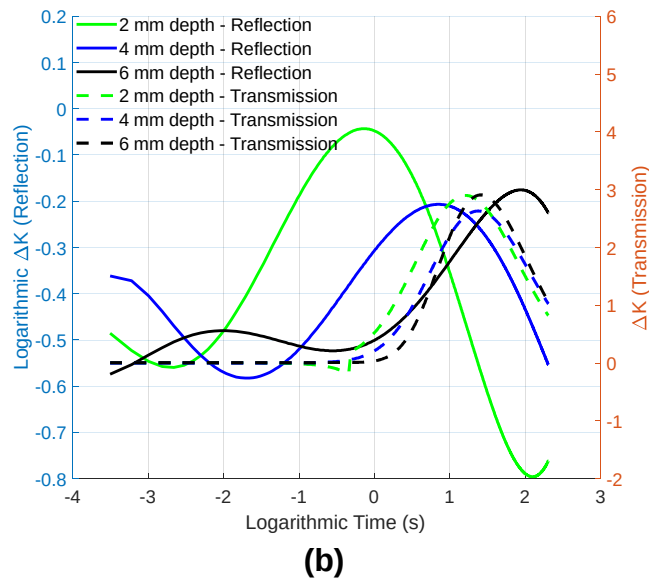
than the surrounding medium, to mimic the thermal behaviour of an air gap [198,204]. This method does not accurately represent an air gap, as air is a fluid and its heat transfer mechanisms differ significantly from those in a solid. However, the primary objective was not to replicate the exact physical behaviour of an air gap. Instead, the focus was on analysing the temporal variations in the thermal response caused by the presence of a defect. Given this objective, the simplified modelling approach is considered acceptable.

Due to the challenging nature of manufacturing subsurface airgaps in composite samples, the focus was shifted towards steel samples. Pulsed thermographic inspections conducted in transmission mode confirmed that the increase in effective thermal diffusivity for defects located nearer to the back wall, as observed in the FEM simulations, was accurate. This validation opens a new avenue of research that has not been previously explored in detail. To obtain a more comprehensive understanding of thermal behaviour, experiments in the reflection mode were also performed. However, due to the presence of plugs interfering with the heat flow, the reflection mode experiments were conducted using the rear side of the sample that did not have plugs. To obtain a like-to-like comparison with the FEM, the simulations were repeated with the same configurations as the experiments. The side with the plugs never faced the IR camera. Since the reflection mode has shown to be more sensitive to defect depth [160], the first derivative plots of both the reflection and transmission were plotted together. Observing the combined plots revealed that as the defect appear closer to the backwall, the first derivative curve of the reflection mode moves closer to its transmission mode counterpart.

Since the excitation energy was low in the simulations and experiments ($\approx 500\text{J}$) the peak for the deeper subsurface defects was not visible. Figure 5-1 shows the combined reflection and transmission mode plots for all the defects at 2mm, 4mm, and 6mm (defect thickness was 1mm) where the pulsed excitation energy was 9.6kJ instead of 500J. Observing these figures clearly shows that once the defect is closer to the backwall beyond half of the sample's overall thickness, which in this case was 8mm, the peak of the reflection mode occurs later than the

transmission mode. Although combining the reflection and transmission mode plots provides a better indication of the defect's location within the sample thickness, it does not accurately quantify its depth. Instead, analysis of the first derivative plots can only suggest that the defect lies beyond half the thickness of the sample.

A possible solution for quantifying the defect depth was developed by analysing the Fourier number. As mentioned in the previous chapter, the Fourier number is a dimensionless quantity that describes the relationship between a material's heat diffusion rate to its storage rate. The variable t represents the characteristic time that could be a single value or an array representing a time series.



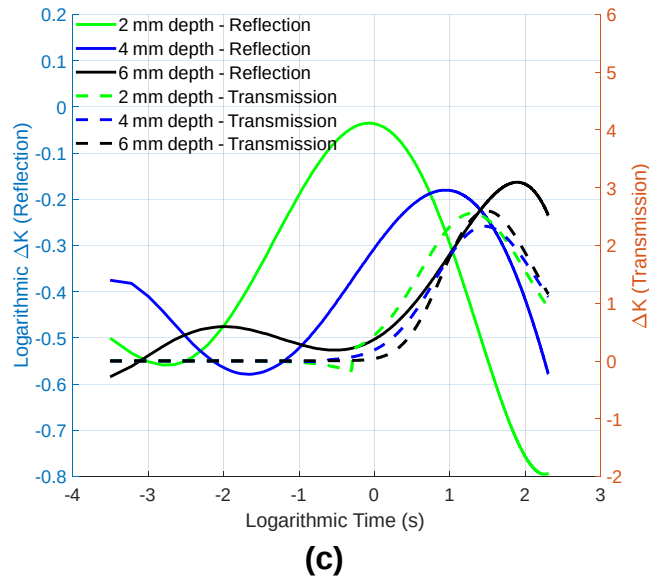


Figure 5-1 Combined reflection and transmission mode plots at 9.6kJ excitation energy for a) 8mm circle, b) 16mm circle, and c) 16mm square at different depths

Using a time series for t can illustrate how the material's ratio of its diffusion rate to its storage rate increases over time while L , the material's characteristic length (either thickness or in our case the defect diameter) remains a constant. Since L is a constant, the change in Fourier number is entirely dependent on the material's thermal diffusivity α and the characteristic time t . To establish a relationship between the defect depth and the Fourier number it was vital to choose an appropriate t . Since Parker's half-rise method has already established the half-rise time as an essential quantity in determining the material thermal diffusivity, this was chosen to be the characteristic time. Calculating the Fourier number using the effective thermal diffusivity at the defect region as α , the half-rise time as t and the defect diameter as L , a linear relationship was established between the calculated quantity and the defect depth.

Both simulations and laboratory experiments showed that regardless of the defect geometry, a positive correlation is observed between the calculated Fourier number and defect depth. To establish a more accurate relationship between the two quantities, extra defects at 3mm and 5mm were added by modifying the FEM slightly and extracting the backwall temperature behaviour from these regions. It is worth mentioning here that this was only done in the

simulation environment. To obtain a like to like comparison between the simulation and experiments, a new sample with more defects should be created to accurately quantify the relationship between the Fourier number and defect depth. Nevertheless, the closeness between the FEM and experiments provide sufficient evidence that the established relationship is accurate.

Finally, it is important to benchmark the newly proposed methodology against an established technique. For this purpose, the LSD method was chosen in the reflection mode, and the depth estimation errors of both methods were compared. The proposed method exhibited higher accuracy in estimating the depth compared to the reflection mode especially for the defects closer to the backwall, aligning with our current understanding of the superior defect detection capabilities of the transmission mode for defects closer to the backwall. Due to the design constraints of the physical sample, this comparative analysis was conducted exclusively in the FEM environment. An improved sample design to address this limitation is planned for future work. Given the strong agreement between the FEM and laboratory results, it is expected that similar conclusions will be reached in the experimental studies. The findings from this study are vital to further develop the through-transmission technique. Although a method has been established, further studies involving defects of varying sizes, heights, and depths are required to formalise it as a robust approach for defect depth quantification.

While the steel sample contained calibrated defects, the viability of the method for uncalibrated defects was also examined. Since the CFRP samples contain damage incurred from impact testing, verifying the newly proposed method's depth quantification capabilities was not possible since the depths were not known. For this reason, the method was modified slightly to establish a relationship between the Fourier number and impact energy. As explained earlier (Chapters 2–4), CFRPs offer high strength-to-weight ratios, making them widely adopted in industries such as aerospace and defence. This extensive use also exposes them to impact damage from sources like projectile fragments [214] highlighting the need for reliable NDT methods to assess structural integrity. In

response, thermographic techniques have advanced considerably in characterising such damage [69,215]. However, most research to date has concentrated on the reflection mode, with limited exploration of the transmission mode. Among the few studies that do investigate transmission mode [4,165], the integration of advanced AI-based algorithms for automated pattern recognition is notably absent. In contrast, reflection mode has demonstrated the successful application of such algorithms for damage detection [164,216]. Given transmission mode's superior lateral and depth resolution, combining it with AI could significantly enhance pulsed thermography's pattern recognition capabilities. Moreover, further development of through-transmission techniques could support integrated dual-mode inspection systems, leveraging both reflection and transmission modes for improved data fusion, image reconstruction, and automated damage assessment. The findings from Chapter 4 provides a greater incentive for researchers to explore the through-transmission technique for automated pattern recognition in the transmission mode, something that is lacking in existing literature. Furthermore, since it was mentioned in Chapter 3 that the spectral emission can have an effect on the accuracy of the estimations (See section 3.4.3), a comparative analysis was performed using the longwave and mid-wave IR cameras. The analysis showed that the longwave camera in the TF configuration yielded the most accurate results in terms of the impact energy estimation.

To qualitatively assess the NLSF algorithms fitting capabilities a residual analysis was performed. Contrary to the steel samples, the fitting conducted on the temperature information obtained from the CFRP samples exhibited noticeable systematic deviation in the form of sinusoidal waves. Further investigation was conducted by fitting a sine wave on the residual plots and an ACF plot was generated to evaluate the extent of this systematic shift. By conducting this analysis, it was revealed that while statistically the NLSF algorithm was able to capture the backwall temperature rise fairly accurately (as indicated by the R^2 and RMSE values), minor systematic deviations were present. These discrepancies could result from boundary effects, infrared sensor behaviour, or the assumptions made in the simplified one-dimensional heat conduction model.

Further investigation would need to be conducted in order to reduce this shift. This could include developing a more accurate mathematical model that can effectively capture the boundary effects and account for the discrepancies resulting from the infrared sensor behaviour. Moreover, key machine learning and AI models, can be leveraged to enhance and optimise the existing model.

5.4 Research Impact

With Big Data, the Internet of Things, Decentralised Decision-Making, Additive Manufacturing, Automation, and Digitalisation being key themes of Industry 4.0, the requirement for large amounts of reliable data is crucial. In particular, accurate estimation of thermal material properties, such as thermal diffusivity, plays a vital role in enabling predictive maintenance, optimising manufacturing processes, and the development of intelligent decision-making systems. By improving the reliability and precision of thermal diffusivity measurements, this work contributes directly to the data-driven foundations required for advanced Industry 4.0 applications, where real-time monitoring and accurate material characterisation are essential. Below is a summary of how the contributions of this work align with several key areas of Industry 4.0:

- **Big Data:** Instruments that can deliver accurate thermal diffusivity measurements improves the quality of datasets used for material behaviour modelling and machine learning algorithms. As high-resolution imaging and faster data acquisition enabled by advanced sensors lead to increased data volume, the need for big data solutions becomes increasingly evident [217].
- **Internet of Things:** Accurate thermal property estimation supports more reliable sensor-driven monitoring systems, enabling real-time decision-making. For larger assets, it also allows for wider and more effective thermal assessment coverage [218,219].
- **Digital maintenance:** Digital solutions like digital twins and augmented reality are changing how maintenance is carried out. By combining these tools with sensor data such as thermographic images, it is possible to spot thermal-related issues or structural

changes early, without needing constant physical inspections. These technologies help teams make better decisions by showing real-time conditions visually, often through AR overlays, and support a shift towards more efficient, preventative maintenance in line with Industry 4.0 principles [219]. In this context, measuring thermal diffusivity adds further value by providing a deeper understanding of how materials respond to heat over time, which can inform predictive models and improve the accuracy of thermal assessments.

- Additive Manufacturing: Thermography can play a key role in additive manufacturing by offering a non-contact method to assess thermal behaviour during and after the production process. It helps to identify potential problems such as uneven heat distribution, material inconsistencies, or thermal stresses that may affect the performance and reliability of printed parts. This type of analysis is especially useful in understanding how printed components interact with external environments or users, supporting better design decisions and quality assurance. As AM continues to grow across industries, thermography presents as a valuable tool for ensuring both functional and ergonomic performance [220]. Precise thermal diffusivity characterisation is critical for controlling process parameters, improving part quality, and reducing defects.
- Automation: High quality thermal material data enhances automated inspection, maintenance scheduling, and process optimisation systems. In the context of this work, previous studies at Cranfield University have established a framework for the automated classification of defects based on pattern recognition [69]. However, it relies on complex image processing algorithms, and the study is conducted solely in the reflection mode. The methodology outlined here provides a simple alternative using the transmission mode albeit with lower accuracy.

6 Conclusion

Through-transmission pulsed thermography was established before reflection mode. However, advancements in technique and practical implementation have progressed more rapidly for reflection mode. This is primarily due to inherent limitations, including the need for access to both sides of the sample, which is often not feasible when the sample is fixed or constrained from one side. Moreover, the most up to date understanding of the transmission mode in terms of defect characterisation is that even though it exhibits superior lateral defect resolution, it cannot quantify defect depth because the thermal wave travels through the full thickness of the material in both defect and defect-free regions.

6.1 Research contribution

The existing body literature lacked a state-of-the-art review of through-transmission thermography. Establishing such a review was identified as a crucial first step for this thesis, as it laid the foundation for developing a methodology to address the current challenges associated with through-transmission thermography. Once the current challenges were identified, the focus of the research shifted towards establishing a robust methodology for evaluating the thermal diffusivity of materials, a property critical for assessing structural health. The final stage of the research focused on addressing the most critical challenge: the quantification of defect depth. A review of the existing literature suggested that a potential solution could lie in establishing a relationship between the Fourier number and defect depth. Developing this relationship enabled more accurate depth quantification, outperforming the use of the LSD method obtained through the basic TSR in the simulation environment. Moreover, the methodology assesses impact energy levels and could be extended to include automated pattern recognition of the damage in the transmission mode, an aspect not currently addressed in the existing literature. The research contributions resulting from this thesis can be summarised as follows:

- Identified the current gaps in through-transmission pulsed thermography by conducting a systematic review of the current-state-of-the-art (See Chapter 2). [Objective 1]
- Developed a methodology for thermal diffusivity evaluation using a full factorial DoE and evaluated its accuracy in both FEM and laboratory experiments (See Chapter 3). [Objective 2]
- Extended the FEM model to include subsurface airgaps and designed a calibration sample containing subsurface airgaps so that the findings from the FEM can be experimentally verified (See Chapter 4). [Objective 3]
- Proposed a novel methodology to quantify the defect depth in through-transmission pulsed thermography by establishing a relationship between the Fourier number and defect depth. The accuracy of the proposed method was verified by comparing it with an established method i.e., LSD (See Chapter 4). [Objective 4]
- Assessed the proposed methodology's feasibility for quantifying impact damage in CFRPs (See Chapter 4).
- Published the raw thermograms alongside the published manuscripts to allow other researchers to benefit from the findings of this work

As emphasised in the previous chapters, although this research provides a transparent and repeatable methodology for measuring thermal diffusivity and extends it to defect depth quantification, it is not without limitations. Accordingly, the following points summarise the limitations identified in this thesis and suggest directions for future research to address them:

- While the systematic review covers the current-state-of-the art, it will have to be periodically updated so that it encompasses new developments around through-transmission thermography.
- To improve the methodology for thermal diffusivity measurement, multiple samples of each thickness should be used to obtain a more accurate and reliable assessment of thermal diffusivity estimation.

- For depth quantification, a broader analysis incorporating various defect shapes, sizes, and depths should be conducted to thoroughly assess the proposed methodology. Additionally, its performance should be compared against other depth quantification methods to evaluate its feasibility and robustness.
- In terms of impact damage assessment, the methodology presented here utilises the temperature profiles of both the sound and defect areas to estimate the impact energy level. As noted earlier (see Section 5.4), current pattern recognition methods for impact-damaged CFRP samples rely exclusively on the reflection mode [69]. The findings from this thesis can serve as a foundation to extend automated pattern recognition capabilities to the transmission mode as well.
- The residual analysis revealed minor systematic deviations in the NLSF method's ability to accurately fit the observed backwall temporal response. This can be improved by either developing a more accurate mathematical model to describe the backwall temperature pattern or using a correction factor to account for the systematic deviations.
- The NLSF algorithm not only outperforms the conventional Parker method in thermal diffusivity estimation but also shows strong potential for data reconstruction. This capability could enable dual-mode reconstruction leveraging both reflection and transmission configurations, extending its application beyond parameter estimation (such as thermal diffusivity and input energy) to enhanced thermal image generation.

6.2 Future Work

While the previous subsection outlined potential future directions, these were primarily linked to the limitations of this study. Nonetheless, the overall outcomes of this research provide a solid foundation for further investigations that extend beyond the scope of this thesis and pulsed thermography itself. The following

outlines several potential research areas that could be explored. This list is not exhaustive, and other directions may also be considered:

- This research has solely focused on the transmission mode with the reflection mode analysis being conducted solely for comparison purposes. Additional research can be conducted by performing a dual-mode inspection and developing a methodology to integrate the data obtained from both modes. This would leverage the advantages offered by each mode while potentially reducing or even eliminating the drawbacks of single-mode inspections.
- The FEM models generated in this study were exclusively for PT. However, the close agreement between FEM results and laboratory experiments validates the use of FEM to simulate more complex structures and explore different heating methods. This, in turn, enables a deeper understanding of the heat transfer mechanisms in materials. Furthermore, as FEM becomes more accurate, it can increasingly reduce the reliance on physical testing, contributing to more sustainable manufacturing and testing processes.
- While this study demonstrated the feasibility of measuring defect depth using through-transmission pulsed thermography, further research is needed to validate the proposed method. This should include mesh sensitivity analysis of the FEM model, along with a broader sensitivity analysis of the experimental results, including but not limited to the influence of lateral defect size on depth quantification accuracy.
- The development of the sample with calibrated airgaps is not exclusively limited to PT inspection. Table 2-1 has listed various active thermography methods that could benefit from using this type of sample. Moreover, PT inspections inherently face depth limitations, as the short-duration pulse cannot deliver sufficient energy for thermal waves to penetrate components of greater thickness. Longer heating times have been shown to enhance the depth resolution of thermography as mentioned in Chapter 2.

Research can be conducted in the transmission mode by leveraging the benefits offered by longer heating times to further develop the through transmission technique.

- Due to the difficulty of current CFRP manufacturing techniques, the calibrated sample was made from steel. However, as advanced manufacturing techniques are being developed, these methods can be explored in the context of developing similar samples for CFRPs allowing for a more comprehensive analysis of the depth quantifications using through transmission thermography.
- One of the key technological advancements emerging from Industry 4.0 is AI. As AI is increasingly integrated into various NDT techniques, it holds significant potential to enhance the accuracy of data analysis in this research. Moreover, AI can be employed to develop more advanced mathematical models for through-transmission thermography, enabling more accurate characterisation of backwall temporal behaviour.
- Finally, hybrid NDT solutions that leverage multiple techniques have not been explored in this thesis due to time constraints. Future work could investigate the integration and compatibility of additional NDT methods to enhance the material and defect characterisation capabilities established in this study.

This thesis has attempted to advance the technique of through-transmission pulsed thermography by establishing a foundation for reliable subsurface defect detection and thermal characterisation. The work provides a platform for future exploration into AI-driven analysis, improved modelling accuracy, and the integration of complementary NDT methods to further enhance the depth, precision, and applicability of PT across complex material systems.

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Appendices

Appendix A Ethical approval letter



11 May 2022

Dear Mr Zain Ali ,

Reference: CURES/15528/2022

Title: Developing a multimodal active thermography system for defect characterisation.

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/15528/2022 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team



20 May 2025

Dear Mr Zain Ali ,

Reference: CURES/25218/2025

Project ID: 17840

Title: Developing the through-transmission technique in pulsed thermography for material characterisation

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your project title change request, reference CURES/25218/2025 has been approved.

If you have any queries, please contact CURES Support.

Regards,

CURES Team

Appendix B Current Landscape of IRT

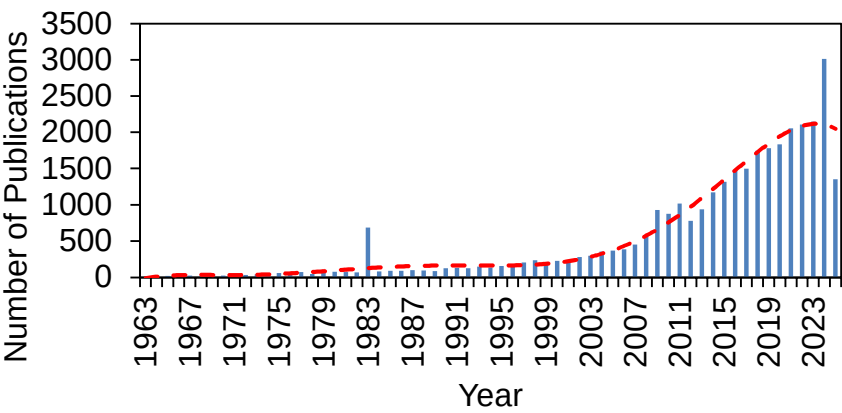


Figure B-1 Number of IRT related publications from 1963 to 2025

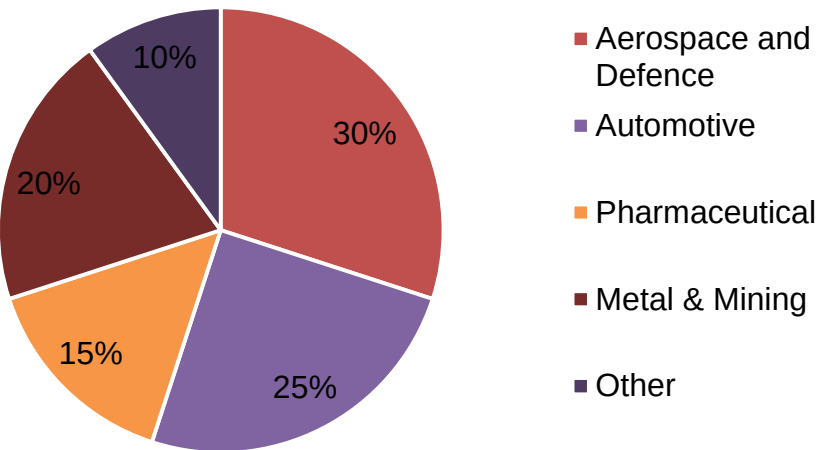


Figure B-2 Infrared thermography market share by end user 2024. (Graph generated using data obtained from [221])

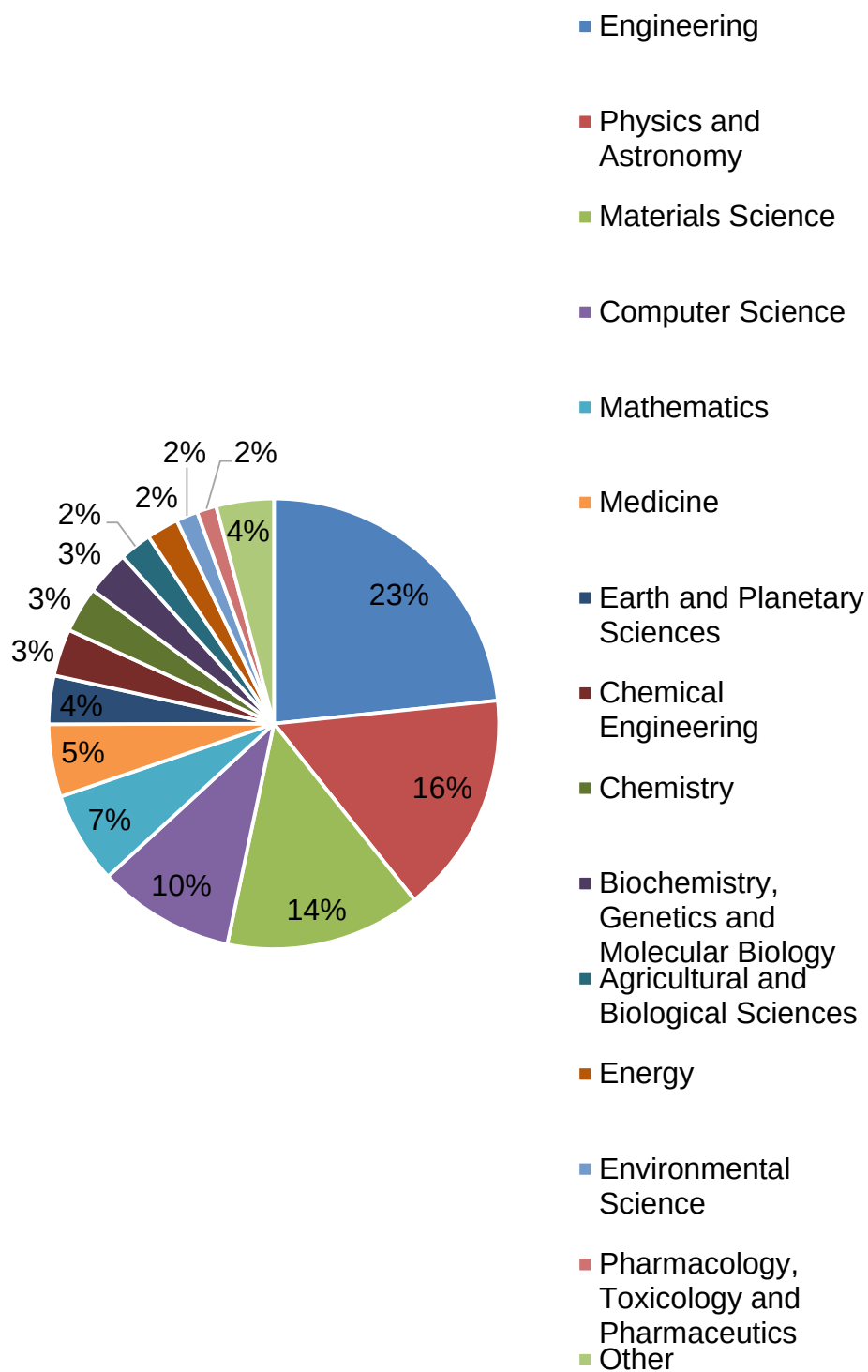


Figure B-3 IRT applications by subject area

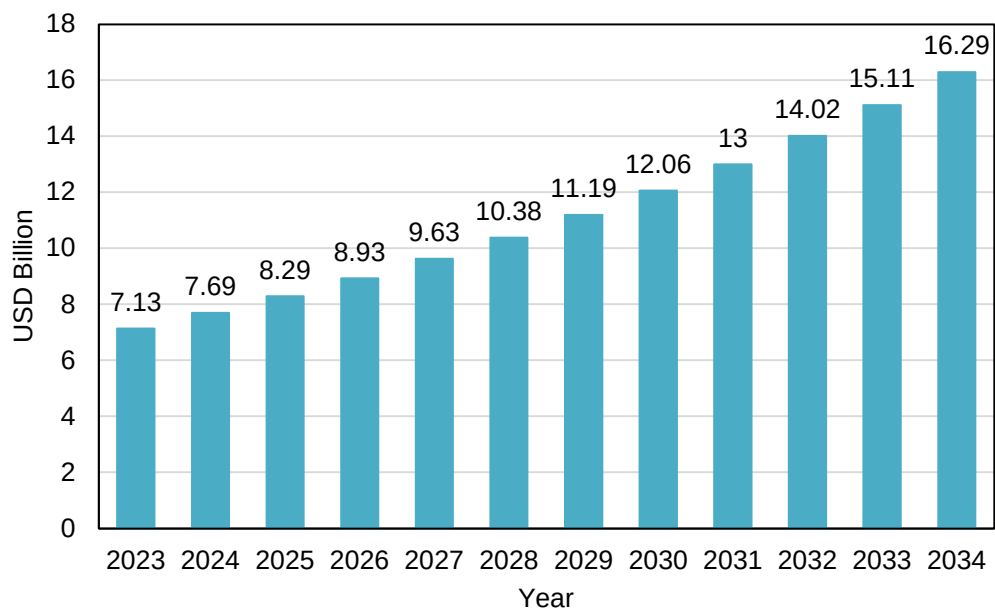


Figure B-4 Global thermal imaging market size (Figure generated on Excel based on data from [222])

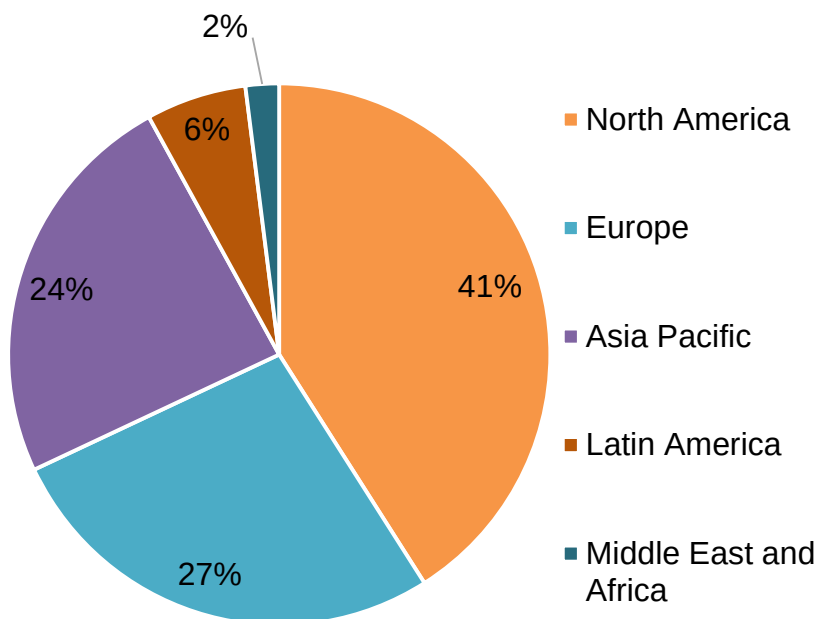


Figure B-5 Thermal imaging market share by region (Figure generated on Excel based on data from [222])

Appendix C Current Landscape of PT

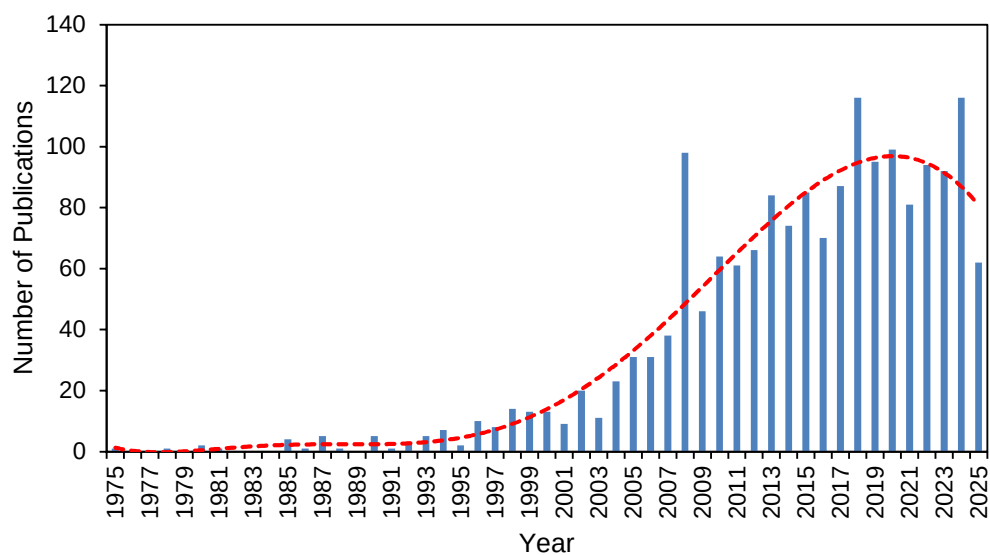


Figure C-1 Number of publications per year using the search strings "pulsed" and "thermography"

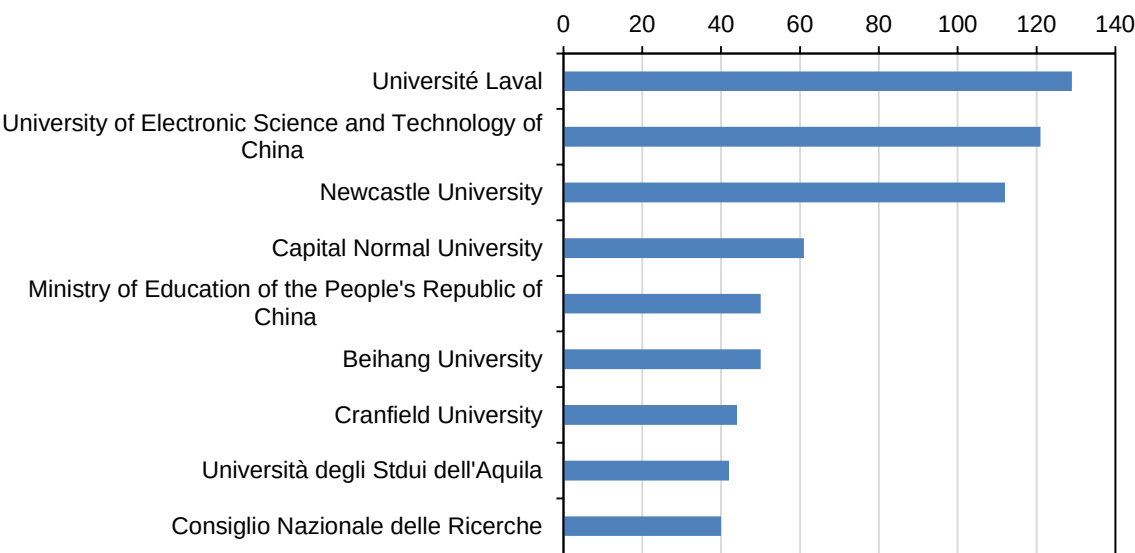


Figure C-2 Pulsed thermographic research by affiliation

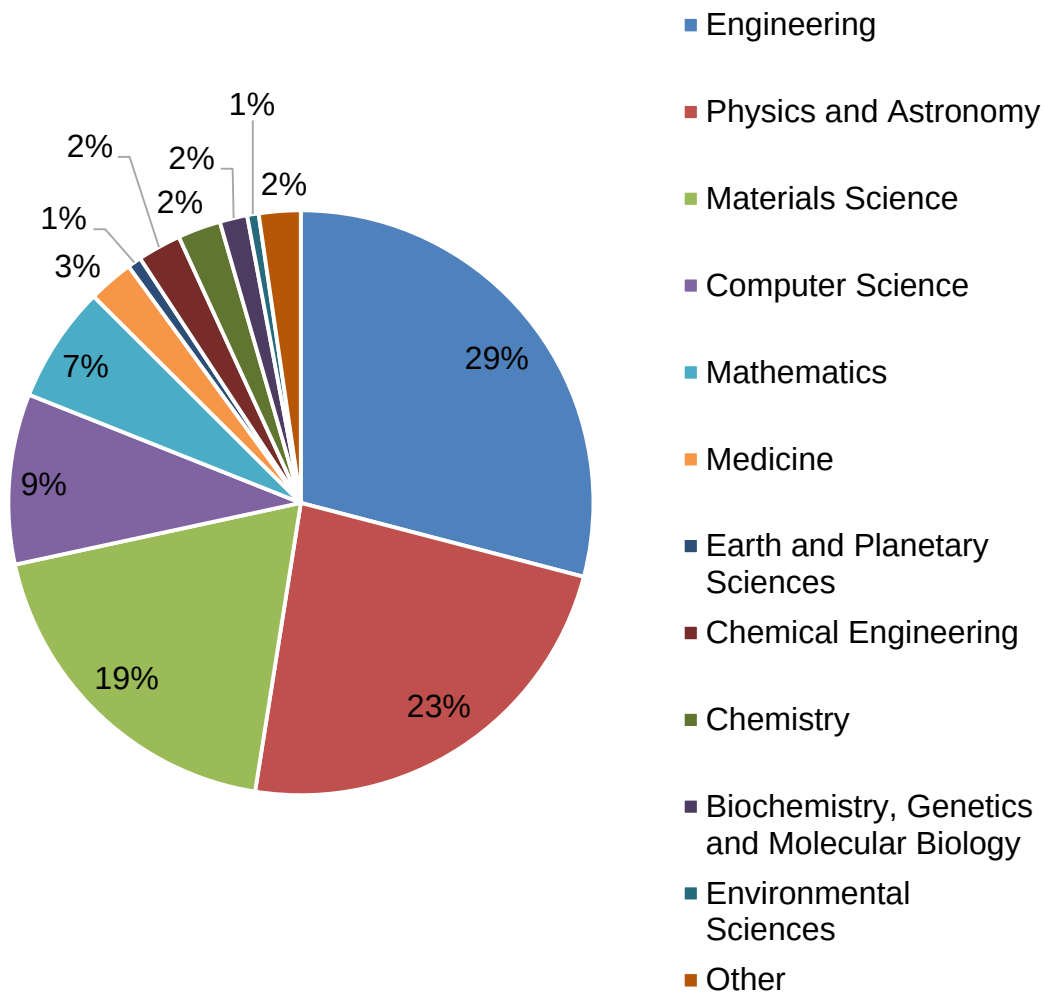
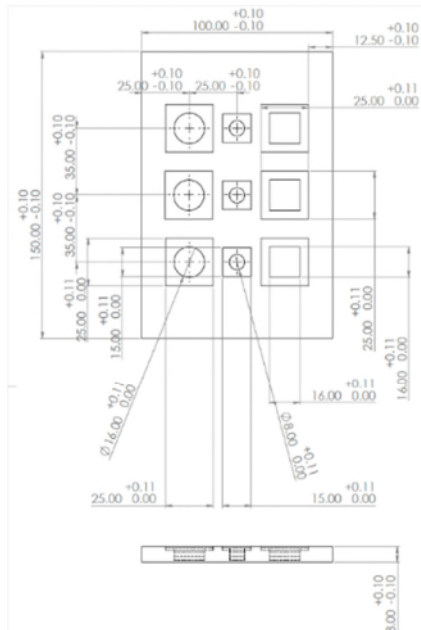
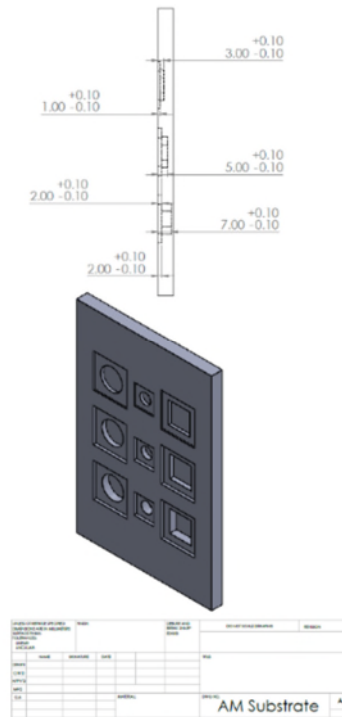
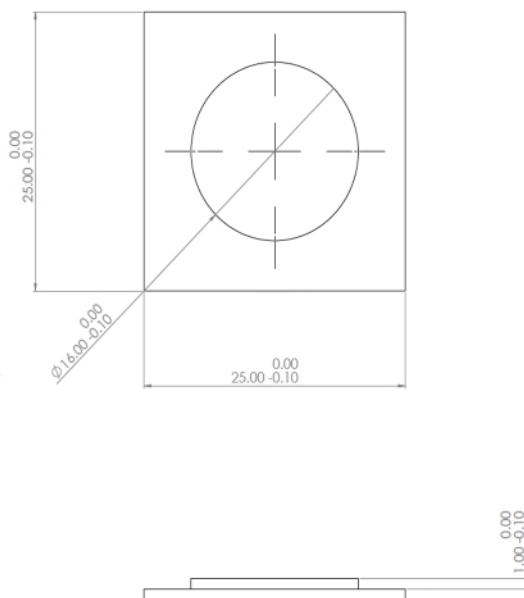
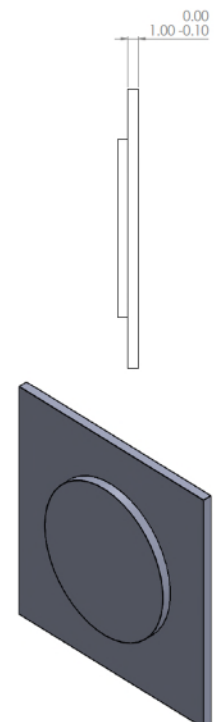


Figure C-3 PT applications by subject area

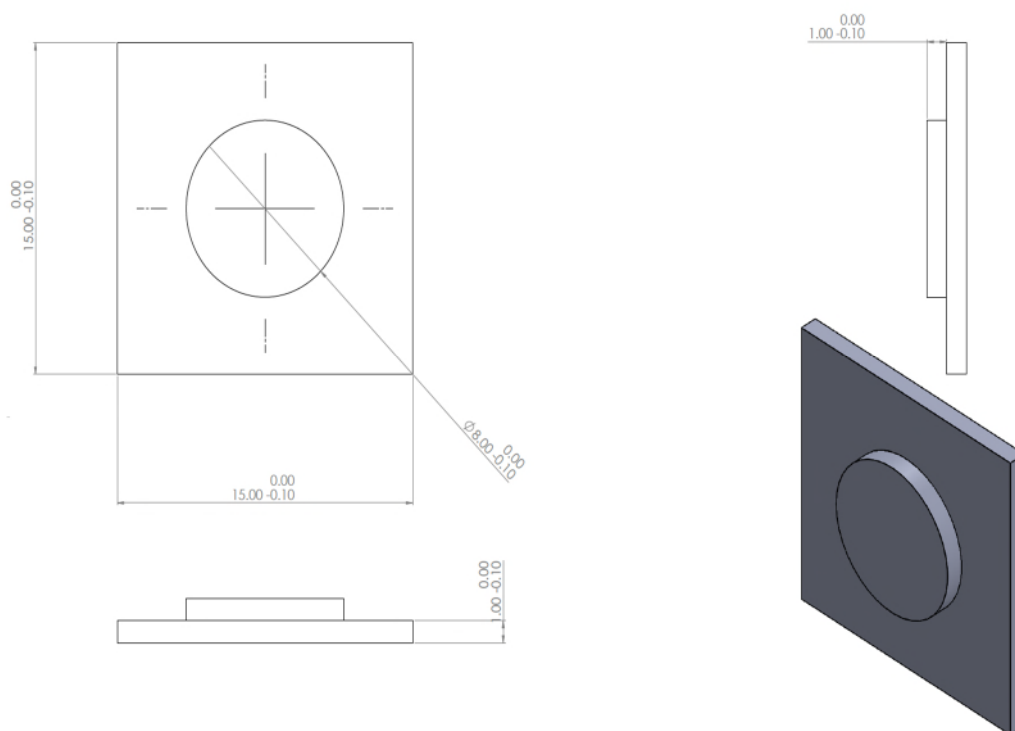
Appendix D Schematic for machined samples



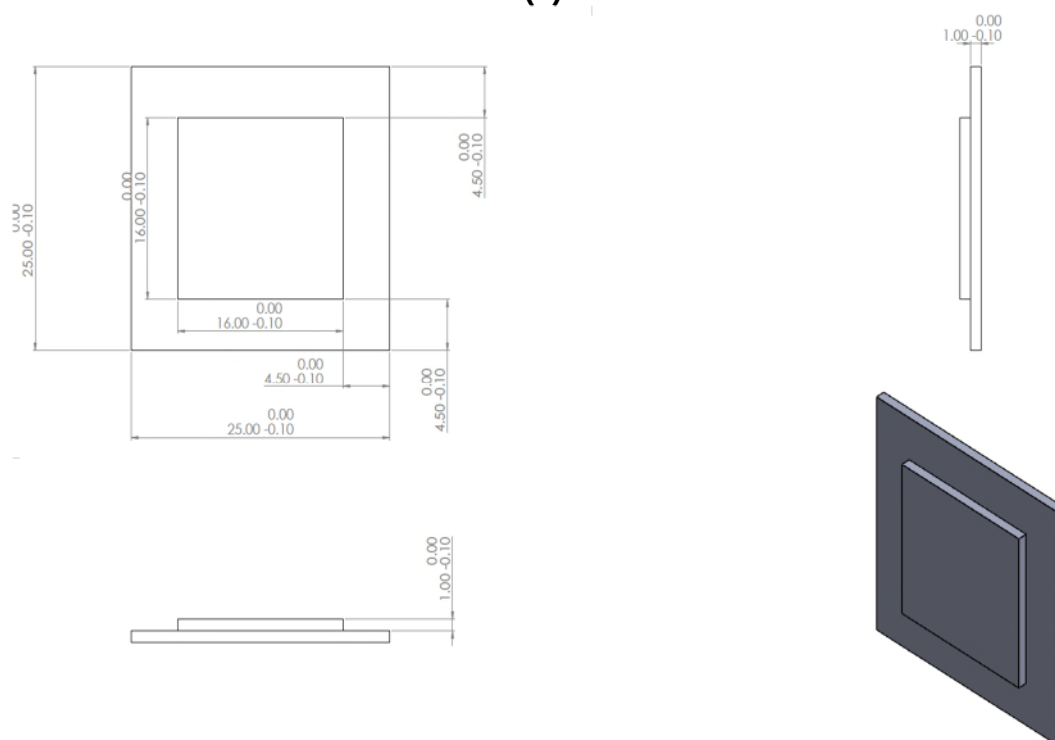
(a)



(b)



(c)



(d)

Figure D-1 Substrate with machined holes at different depths b,c,&d) Plugs for the first three holes showcasing all the different defect shape and sizes (all dimensions are in mm)

Appendix E Email confirming manuscript submission

MEAS-D-25-06517 - Confirming your submission to Measurement

 em.meas.0939873.8723eb60@editorialmanager.com on behalf of Measurement <em@editorialmanager.com>
To: Zain Ali
Click here to download pictures. To help protect your privacy, Outlook prevented automatic download of some pictures in this message.

 Reply  Reply All  Forward 

Fri 23/05/2025 20:10

Dear Mr. Ali,

Thank you for sending your manuscript Defect depth estimation using through-transmission pulsed thermography: A numerical and experimental investigation for consideration to Measurement. Please accept this message as confirmation of your submission. It has been assigned the following manuscript number: **MEAS-D-25-06517**.

When should I expect to receive the Editor's decision?

We publicly share the average editorial times for Measurement to give you an indication of when you can expect to receive the Editor's decision. These can viewed here: http://journalinsights.elsevier.com/journals/0263-2241/review_speed

What happens next?

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1. First, your manuscript will be assigned to an Editor and you will be sent a unique reference number that you can use to track it throughout the process. During this stage, the status in EM will be "With Editor".

2. If your manuscript matches the scope and satisfies the criteria of Measurement, the Editor will identify and contact reviewers who are acknowledged experts in the field. Since peer-review is a voluntary service, it can take some time but please be assured that the Editor will regularly remind reviewers if they do not reply in a timely manner. During this stage, the status will appear as "Under Review".

Once the Editor has received the minimum number of expert reviews, the status will change to "Required Reviews Complete".

3. It is also possible that the Editor may decide that your manuscript does not meet the journal criteria or scope and that it should not be considered further. In this case, the Editor will immediately notify you that the manuscript has been rejected and may recommend a more suitable journal.

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If you need to retrieve password details, please go to: http://ees.elsevier.com/MEAS/automail_query.asp

2. Click on [Author Login]. This will take you to the Author Main Menu
3. Click on [Submissions Being Processed]

Many thanks again for your interest in Measurement.

Kind regards,
Measurement

If you require further assistance, you are welcome to contact our Researcher Support team 24/7 by live chat and email or 24/5 by phone: <http://support.elsevier.com>

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