

CRANFIELD UNIVERSITY

Lydia Frumosu

In Process Temperature Monitoring of Energy Beam Processing

School of Aerospace, Transport and Manufacturing

MRes Manufacturing
Academic Year: 2018 - 2019

Supervisor: Dr Zhaorong Huang
Associate Supervisor: Dr Claudiu Giusca
July 2019

CRANFIELD UNIVERSITY

School of Aerospace, Transport and Manufacturing

MRes Manufacturing
Academic Year: 2018 - 2019

Lydia Frumosu

In Process temperature monitoring of Energy beam processing

Supervisor: Dr Zhaorong Huang
Associate Supervisor: Dr Claudiu Giusca
July 2019

This thesis is submitted in partial fulfilment of the requirements for
the degree of Masters by Research

© Cranfield University 2019. All rights reserved. No part of this
publication may be reproduced without the written permission of the
copyright owner.

ABSTRACT

The use of non-thermal and atmospheric plasma has been growing in recent years. Applications in wound sterilisation, food decontamination, cleaning and the more traditional machining and deposition are just some of the areas in which new technology is being developed. With the growing use of cool plasma comes the requirement to test and understand the temperature distribution of the jets. Current methods into temperature measurement revolve around spectroscopy and other non-contact methods. Spectroscopy can pose a challenge as a measurement device as it lacks the ability to measure overall gas temperatures in non-thermal plasmas. Contact measurement thermometers, such as thermocouples and resistance temperature detectors are an alternative which can provide an insight into the temperature of the ions and neutral species. However these sensors pose a challenge in gaining accurate or precise temperature measurements due to their susceptibility of electromagnetic interference.

Fibre Bragg grating sensors have the ability of measuring both temperature and strain without electromagnetic interference. They possess the ability of multiplexing, being able to measure multiple temperatures across a single fibre, which can aid in measuring over a long distance. They also have the added benefit of being small, lightweight and have quick thermal response times. Additionally their small heat capacity reduces the effect on the temperature of the measurand, improving their accuracy over other physical probes. In this experiment fibre Bragg grating sensors 600 μm and 1000 μm in length and 10 μm in diameter have been used to characterise the temperature distribution of non-thermal microwave plasma and thermal radio frequency plasma jets. Thermocouples have been used to compare results against current technologies. Results show the fibre Bragg grating sensors have been successful in determining plasma temperature changes over time, distance and across a variety of different parameters.

Keywords: Fibre Bragg Gratings | Atmospheric Plasma| Non Thermal | Thermocouple

ACKNOWLEDGEMENTS

I would like to thank my supervisors, lab technicians, friends and family for the support.

I would like to thank my supervisors Dr Zhaorong Hung and Dr Claudiu Giusca, for the continued support they have provided over the past 6 months. They have been a great deal of support and guidance throughout my thesis. I have never felt afraid to go for them I needed help, for which I am truly grateful. They helped me to stay confident, focused while also being independent. I feel they have prepared me for a bright future in research.

I would like to extend my thanks to the building 70 laboratory technicians, Alan Hume and John Hedge who have been very helpful in helping me to produce my substrates and torch mountings. Not only have this but they been a friendly face, helping to create a happy lab environment. I would also like to thank Tim Pryor from building 50 who helped support me in calibrating my instruments using the facilities oven.

I would like to give thanks to Dr Adam Bennett for teaching me to use the equipment, even during busy times. Not to mention assisting with me through my learning process of understanding microwave plasma.

I would like to thank my colleges for supporting me throughout this past year, particularly Katherine Gobey, Alex Bishop and Sara Hawi. As I don't have a physics or engineering background, they were an amazing help to explain to me things I didn't yet understand. Not to mention they made my past year a lot of fun!

Thank you to my partner, Jack White, for being especially supportive when I was the most stressed. You truly are the kindest man I have ever met.

Finally I would like to thank my family for the continuous support they have given me my whole life. Without their encouragement I would have never been able to believe in myself and peruse research. Not to mention being a supportive family, who I consider not just relatives but friends. Thank you especially to my parents, Amanda Marton and Mihai Frumosu for really supportive for this past year!

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS	ii
LIST OF FIGURES	v
LIST OF TABLES	ix
LIST OF EQUATIONS	x
LIST OF ABBREVIATIONS	xi
1 Introduction	1
1.1 Research Focus.....	1
1.1.1 Context.....	1
1.1.2 Research Gap.....	2
1.2 Overall Aim	3
1.3 Objectives	3
2 Literature Review	4
2.1 Plasma.....	4
2.1.1 Atmospheric Plasma	8
2.2 Temperature Sensing	9
2.2.1 Methods of Heat Transfer.....	10
2.2.2 Temperature Measurement.....	10
2.3 Thermocouples	11
2.3.1 Thermocouples in Plasma.....	11
2.4 Fibre Optic Sensing	13
2.4.1 History of Fibre Optic Sensors	15
2.4.2 Applications and advantages of fibre optic sensing.....	16
2.5 Fibre Bragg Gratings.....	16
3 Methodology	20
3.1 Materials and Equipment	26
3.1.1 Materials.....	26
3.1.2 Equipment.....	26
3.2 Methods	27
3.2.1 Calibration	27
3.2.2 Mercury Thermometer.....	33
3.3 Experimental Methods	35
4 Results	37
4.1 Non-Plasma Temperature Measurement.....	37
4.1.1 Static Strain-induced Measurements.....	37
4.2 Dynamic strain induced measurement.....	42
4.3 Sensor Response Times.....	44
4.3.1 Thermocouple Response Times.	44
4.3.2 Fibre Bragg Grating temperature measurement response times	50

4.4 Surface structure visualisation	51
4.5 Static Temperature Measurements.....	53
4.5.1 Temperature Measurements over time	53
4.6 Z height Experiments	58
4.6.1 Thermocouples	58
4.6.2 Fibre Bragg Gratings.....	59
4.7 Spatial Profiles of the plasma temperature (Microwave cold plasma).....	61
4.7.1 Thermocouples	61
4.7.2 Fibre Bragg Grating.....	63
4.8 Temperature Profiles (radio wave thermal plasma)	71
5 Discussion	73
5.1 Non Plasma Temperature measurements	73
5.2 Response times	74
5.3 Surface structure effects	74
5.4 Static Temperature Measurements.....	75
5.5 Z height Experiments	78
5.6 Temperature Profiles	79
6 Conclusions and future work	80
6.1 Conclusion	80
6.1.1 Future work	80
7 REFERENCES.....	82
APPENDICES	92
Appendix A Fibre Bragg grating images	92
Appendix B	93
Appendix C	94
Appendix D	95

LIST OF FIGURES

Figure 1 displays the relation between electron density and temperatures in a variety of different plasma environments (Cao 2010)	7
Figure 2a (left) displays a cross section of a single mode fibre consisting of a high refractive index core and lower refractive index cladding. Figure 2b (right) displays internally reflected light propagating along a fibre. (Amos, 2018) 13	
Figure 3 displaying a fibre Bragg grating within a fibre core (Cusano <i>et al</i> 2019).	18
Figure 4 shows the Plasma Tact vertically mounted into the RAPT300 machinery.	21
Figure 5 shows the setup of the RF temperature measurement experiments. The RAPT300 in built thermocouple was used to measure the air temperature around the plasma.	22
Figure 6 displaying the effect of cool microwave plasma at 15W and 5Lmin flow rate on Tufnol.	23
Figure 7 displaying the PTFE substrate with fibre Bragg grating sensor attached. One 0.3mm wide groove was milled into the substrate at a depth of 0.25mm.	23
Figure 8 displays the MACOR substrate with two FBGS attached. Two 0.3mm wide grooves were milled into the substrate at a depth of 0.25mm.	24
Figure 9 showing the temperature readings of 4 thermocouples over time. TCs were placed in boiling water for 1500 seconds. Note the temperature scale does not start at zero.	28
Figure 10 showing the temperature readings of 4 thermocouples over time. TCs were kept at room temperature for 1500 seconds. Note the temperature scale does not start at zero, and has a temperature range from 19°C to 22°C..	29
Figure 11 shows the temperature reading of TC5 in ice water over 150 seconds. The reading shows an average temperature of 0.32°C with a standard deviation of 0.0648.	30
Figure 12 Reflection Spectrum of Fibre Bragg grating Sensor A at 25°C	31
Figure 13 displaying temperature measurement taken by a mercury thermometer.	34
Figure 14 displaying the Plasma tact emitting a non-thermal microwave plasma jet.....	35
Figure 15 displaying the FR torch emitting a plasma jet upon the FBGS	36
Figure 16 FBGS temperature measurement of room temperature argon gas, at varying flow rates. Results were taken over a 200 second time frame and at	

10 measurements per second. Note that the variation between temperatures is less than 1°C.....	38
Figure 17 Experiments show that higher flow rates slightly lower the temperature reading at room temperature conditions, with the presence of an extractor fan.	39
Figure 18 displaying the difference between FBGS measurment in ambient air with and without effect of the extractor fan. These measurments were compared with measurments of ambient temperature argon gas in the center of gas flow diameter at 5L/min over time.	40
Figure 19 contrasts FBGS temperature measurments acorss three different conditions, where no gas flow was passed through the torch. Figure 19a (top left) show the temperature measurment of a non moving sensor across 2 minutes. Figure 19b (top right) displays the temperature measurment of a non moving sensor across 2 minuites with the extractor fan on. Figure 19c (bottom) presents the temperature measurment of a moving sensor across 10 minuites, moving at 0.5mm/min. (Note this was conducted over a five times longer period of time than the previous measurements in a and b, so the 0.2°C increase in likely caused by a shift in atmospheric temperature rather than the strain caused by the sensor movement).....	42
Figure 20 The temperature measurment of a moving sensor across 20 minuites, moving at 0.5mm/min across a flowing of argon gas at 5Lmin ⁻¹ . Sensor was moved across the Y axis from one side to the other, before returning to the centre of the gas flow before moving to one side of the X axis and back. .	43
Figure 21 displays the reaction times of thermocouples exposed to plasma at various distances away from the jet nozzle. Atmospheric temperatures were recorded for 8 seconds before plasma exposure. Atmospheric temperature was kept at 20°C +/- 1°C	44
Figure 22 displays the response times of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin-1 and power was 15W. Every 30 seconds the z height was decreased by 0.5 mm. This continued until z=0 after 630 seconds.	45
Figure 23 displays the temperature over time of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin-1 and power was 15W. The graph displays response times for Z heights between 10mm to 3mm.(Figure 24 displays the response times at z heights between 0mm to 3mm.) The results show an average thermocouple response time of 5 seconds. They also show that the plasma temperature increases as the z height decreases.	46
Figure 24 displays the temperature over time of various z height thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 2LMin-1 and power was 15W. Z heights range from 3mm to 0mm. The results show an average thermocouple response time of 10 seconds. Unlike at higher z heights, the temperature reading does not continue to increase as z	

height decrease. They show that the plasma temperature increases as the z height decreases from 2mm to 0mm, however this is still a lower reading than at higher z heights. When the Z height decreases from 2.5mm to 2mm the temperature measurment quickly drops to over 90°C less.	47
Figure 25 displays the response times of various thermocouples to an exposure by an argon plasma jet at its centre point. Flow rate was 2LMin ⁻¹ and power was 15W.....	48
Figure 26 displays the response times of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin ⁻¹ and power was 15W. Z heights	49
Figure 27 displaying the response times of a FBGS to exposure by an argon plasma jet at it's center point. Flow rate was 5LMin ⁻¹ and power was 15W. Z height was 2mm.	50
Figure 28 Light microscopy images of the surrounding core of the grating region of a FBGS. Images were taken before plasma processing.....	51
Figure 29 Light microscopy images of the surrounding core of the grating region of a FBGS. Images were taken after plasma proccessioning	52
Figure 30 Temperature measurments of a static thermocouple over 1 minuite. Results show lower flow rates produced lower temperature readings.	55
Figure 31 Reflected wavelength measurments of a static FBGS over 1 minuite. Results show lower flow rates produced higher temperature readings.....	56
Figure 32 Temperature measurments of a static thermocouple exposed to a plasma jet over 1 minuite, at varied flow rates and power. Results show lower flow rates produced higher temperature readings.	57
Figure 33 displays temperature readings at 100mm and 101mm z height using a FBGS at the center of a MW argon plasma at 1L/min.	60
Figure 34 displays average temperature readings at varying z heights from 100mm to 110mm z height using a FBGS at the center of a MW argon plasma at 1L/min.....	60
Figure 35 displays the X axis temperature profile of a 5L/min, 15W microwave plasma jet, across its 2mm diameter, as measured by a thermocouple. ...	62
Figure 36 displays the X axis temperature profile of a 5L/min, 15W microwave plasma jet, as well as the surrounding air temperature across 10mm , as measured by a thermocouple.	62
Figure 37 displaying an initial train experiment using a FBGS to measure non thermal microwave plasma, unrestrained. The motion stage moved at 10mm min ⁻¹ and the flow rate of the plasma was 5Lmin ⁻¹	64

Figure 38 displays the temperature profile of an argon MW plasma jet using a FBGS across the Y axis. Power was set to 15w and flow rate was 5Lmin ⁻¹ . Results show temperature of the jet ranges from 300 to 350°C.	65
Figure 39 displays the temperature profile of an argon MW plasma jet and surround air using a FBGS across the Y axis over 4mm. Power was set to 15w and flow rate was 5Lmin ⁻¹ . Results show temperature of the jet ranges from 300 to 350°C, while ambient air temperature ranged from 230 to 320°C.	66
Figure 40 displays the temperature profile of an argon MW plasma jet using a FBGS across the X axis. Power was set to 15w and flow rate was 5Lmin ⁻¹ . Results show temperature of the jet ranges from 280 to 350°C	67
Figure 41 displays the temperature profile of an argon MW plasma jet and surround air using a FBGS across the Y axis over 4mm. Power was set to 15w and flow rate was 5Lmin ⁻¹ . Results show temperature of the jet ranges from 280 to 350°C, while ambient air temperature ranged from 220 to 300°C	68
Figure 42 Temperature profiles of the Argon plasma jet across Y. Profiles were taken at the center point (X=0) and at 0.1mm, 0.2mm,0.3mm and 0.5mm from the the center point.....	70
Figure 43 displays the Y axis temperature profile, across 0X axis position.	71
Figure 44 displays the Y axis temperature profiles, across 22 X axis positions ranging from 0mm to +18mm from the centre of the jet. Data shows an average point over 100 results.	72
Figure 45 by Knoerzer et al., (2012) showing the temperature of a measured surface exposed to 1.55mbar pressure and 0.9kW microwave power by thermocouples and a fibre optic phosphor sensor	75

LIST OF TABLES

Table 1 displays the average temperature of 4 thermocouples used to measure boiling water.	28
Table 2 describes the average wavelengths recorded using a FBGS at various conditions; Ice water, room temperature, boiling water	32
Table 3 describes the scale factors (to 3.s.f) calculated where $\Delta\lambda_B$ is calculated using the average wavelengths at two different temperatures.....	32
Table 4 displays the temperature reading of a mercury thermometer at varying Z heights.	33
Table 5 showing the temperature readings of the 0.6mm length FBGS under an argon flow at various flow rates. Results do not seem to show a correlation between gas flow rate and recorded gas temperature.....	38
Table 6 the average temperature reading from the FBGS of pure argon gas at multiple flow rates, in the presence of an extractor fan.....	39
Table 7 displays the average temperature of the FBGS measurment in ambient air with and without effect of the extractor fan, as well as ambient temperature argon gas in the center of gas flow diameter at 5L/min over time. Results show that there may be a slight increase in temperature measurment under a flow rate, although the difference in temperature is too small to be significant.....	41
Table 8 displays the parameters used in terms of flow rate and power for each experiment. Although the power input into the system was easily controlled, the power reflected was harder to control, resulting in varied overall powers. The highest possible efficiency with a stable overall power was chosen in each case.	53
Table 9 displays a comparison of the temperature recorded from a FBGS, of two various Z heights, in measuring the effect of flow rate and power, in argon plasma jet temperatures.	56

LIST OF EQUATIONS

(2-1)..... 5

(2-2)..... 5

(2-3)..... 6

(2-4)..... 6

(2-5)..... 9

(2-6)..... 10

(2-7)..... 13

(2-8)..... 15

(2-9)..... 17

(2-10)..... 17

(2-11)..... 17

(2-12)..... 18

(2-13)..... 19

(3-1)..... 20

(3-2)..... 32

LIST OF ABBREVIATIONS

IR	Infrared
FBG	Fibre Bragg Grating
FBGS	Fibre Bragg Grating Sensor
UV	Ultra Violet
EM	Electromagnetic
TC	Thermocouple
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
MV	Microwave frequency
RF	Radiowave frequency

1 Introduction

1.1 Research Focus

1.1.1 Context

The applications of low temperature (0-1000C) electromagnetic (EM) wave plasma has been increasing in the recent years, from the well-known manufacturing techniques of sputtering and etching to younger technologies such as biological decontamination, surface energy modification and the cleaning of surfaces (Lieberman and Lichtenberg 2005) (Niemira 2012) (O’Kane and Mittal 1974) (Wilkinson and Rahman, 2004) (Wolf and Sparavigna, 2010).

Due to the electromagnetic field associated with the plasma jets, knowing the temperature of the jet produced has been difficult. Physical sensors such as thermocouples and resistance temperature detectors are thought to produce unreliable temperature readings (Amiel et al., 2012) (Farias et al 2017) (Knoerzer et al., 2012) (Talyanskii 1992).

Non-contact thermometers can be utilised to overcome these problems. However they are unable to provide information regarding a particular point in the gas without the use of tomography. Another limitation is that they only provide information regarding the electron temperature, as they detect IR radiation they are unable to provide information regarding the temperature of other particles within the gas (Jakubowski et al., 2011) (Wuilloud et al., 2004).

Glass Fibre sensors have been considered as a method to overcome this as they are unaffected by the EM field. As a physical sensor they will be able to read the temperature within a plasma jet, as well as provide an indication on the overall temperature of the gas.

Fibre optical sensors are made of either glass or polymer, making them suitable for a wide array of environments. Glass sensors have been found to be useful in chemically reactive, high temperature environments and such are used heavily in the oil and gas industry.

1.1.2 Research Gap

The temperature of both thermal and non-thermal Electromagnetic (EM) wave plasma is often measured through non-contact measurement techniques such as optical emission spectroscopy (OES). In non-thermal plasmas this results in only the electron temperatures being known as the electron, gas and neutral species temperatures are different. Physical probes pose the possibility for measurement of the overall plasma temperature but suffer from electromagnetic interference (Corre et al., 2018).

Some experimentation has been made into forms of fibre optic measurement within plasma to success however there is a significant deficit in research into the use of Fibre Bragg gratings in atmospheric plasma as a temperature measurement device. Niewczas *et al*, (2008) presented a paper for “Concept level evaluation of the full-scale deployment of fibre Bragg grating sensors for measuring forces in JET during plasma disruption events”. Here FBGS were used for their ability to measure strain and pressure rather than temperature. Corre et al., (2018) used FBGS to measure the temperature of plasma facing components in a long pulse tokamak. The study showed promising results when compared to a thermocouple, with the possibility to acquire similar temperature measurements without electromagnetic disturbance.

This however occurred in a highly magnetic vacuum rather than atmospheric conditions and so does not accurately describe the FBGS ability to be used as a physical probe in MW and RF plasma for manufacturing.

1.2 Overall Aim

To evaluate the use of fibre Bragg gratings for measuring the temperature in atmospheric plasma jet processing as a contact thermometric device.

1.3 Objectives

1. To test the ability of a FBGS to measure the absolute temperature within atmospheric plasma.
 - Ensure FBGS does not undergo considerable interference from the conditions related to ionised gases, as well as the effects of changes in pressure or, with the case of FBGS, strain.
 - Design FBGS mounting methods which would ensure rigidity and reduce physical interference of the jet.
2. To compare temperature measurements taken from thermocouples and FBGS.
 - Use both thermocouples and FBGS to measure temperature profiles across a microwave plasma jet.
 - Use both thermocouples and FBGS to measure temperature changes over time, in order to observe temperature stability within a microwave plasma jet.
3. To use FBGS to measure temperature profiles across a radio frequency wave coupled plasma jet.

2 Literature Review

2.1 Plasma

Irving Langmuir first coined the term plasma to define hot ionised gases in 1928. (Roth 1995) Plasma is often considered to be a fourth state of matter, where not only are the bonds between molecules broken to allow free movement, as in a gas, but is also ionised so that the gas composes neutral particles, ions and electrons (Sturrock 1994). In practice a gas will not be fully ionised, however the ratio of ions and electrons to neutral particles can be very high (Spitzer 1956).

An integral component of plasma is the presence of an electromagnetic field (Sturrock 1994). Plasma has the ability to sustain electrical current, while deionised gas is an insulator. It is also capable to support high frequency oscillations. (Thompson 1962).

Some stipulate that to define a plasma, it must have equal electron and ion concentrations, i.e. have a net neutral charge (Ruddy 1975). Debye length, or Debye radius, is a measure of the overall electrostatic effect within a plasma. It is the radius, of a sphere of surrounding field of electric potential around a charged particle. The limits of this sphere being where there is a decrease of magnitude $\frac{1}{e}$, where 'e' is the elementary charge and the electric potential is considered negligible, (Ruddy 1975) (Sillanpää and Shestakova 2017). This occurs due to the cancelling out of surrounding positive and negative charges.

Plasma generation is often related to gas discharge, where electric current flows through a gaseous medium due to the ionisation of the gas (Cao 2010) (Ruddy 1975). Other production methods also include high frequency discharge and high energy particle beam (Taylor 1994). Naturally occurring plasma can be found in the upper atmosphere (ionosphere), in the sun and surrounding stars, as well as

closer to home in the aurora, due to solar wind and lightning, due to accumulated charges. (Cao 2010) (Ruddy 1975).

Electrodes are commonly used to in plasma production, where an arc jet is produced from a negative electrode nozzle, towards a positive column. (Taylor 1994) Radio frequency (RF) EM wave produced torches do not require electrodes as they transfer energy through inductive or capacitive coupling. In inductive coupling, a variable magnetic field maintains the discharge. This is generally contained within a quartz tube enclosed within an RF coil (Yoshida 1990).

Like metals, plasmas conductive properties mean that they reflect certain wavelengths of light. The free electron number density (n_e) determines the behaviour of light within a plasma. This is defined as the number of free electrons per meter cubed. The density of free electrons determines the plasma frequency (ω_p); the oscillation of the electron density caused through instability in the dielectric function. Plasmas only reflect light with a frequency below the plasma frequency, so the denser the plasma the more light it will reflect.

$$\omega_p = 2\pi f_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m}} \quad (2-1)$$

The above formula describes the determinants of plasma frequency where e is electron charge, m is electron mass, ϵ_0 is the permittivity of free space. F_p is the angular plasma frequency (Jessner, 2010)(Tonks and Langmuir 1929) (CSBSJU n.d.) (Wiesemann n.d.).

Plasma can be modelled as an ideal gas providing the potential energy of the electrons and ions is much less than the average kinetic energy.

$$\frac{3}{2} k_B T_e \gg \frac{e^2}{4\pi\epsilon_0 \lambda_n} \quad (2-2)$$

The Langmuir probe is an important tool in ascertaining the electron temperature, density and potential at reduced gas pressures. It consists of a small conductor which collects information regarding the I-V characteristics (current vs voltage trace). (Chen and Chang, 2003)

There are two main concepts accompanying plasma gas. The first is the degree of ionisation which is determined as the electrons densities (n_e) divided by itself plus the densities of neutral atoms (n_n) (Raizer 1991).

$$\text{Ionisation degree} = \frac{n_e}{(n_e + n_n)} \quad (2-3)$$

The second concept is temperature which may be mathematically modelled in gases with accordance to the ideal gas law, which defines the gas temperature as its pressure (p) over density multiplied by the Boltzmann's constant (k) (Cao 2010).

$$T = \frac{p}{nk} \quad (2-4)$$

The temperature of plasma gases is an impression of the particles thermal kinetic energy. Electron temperature (T_e), depending on the electron energy distribution function, is used to demonstrate electron kinetic energy. Figure 1 below shows the relationship between different types of plasma against their density and electron temperature values.

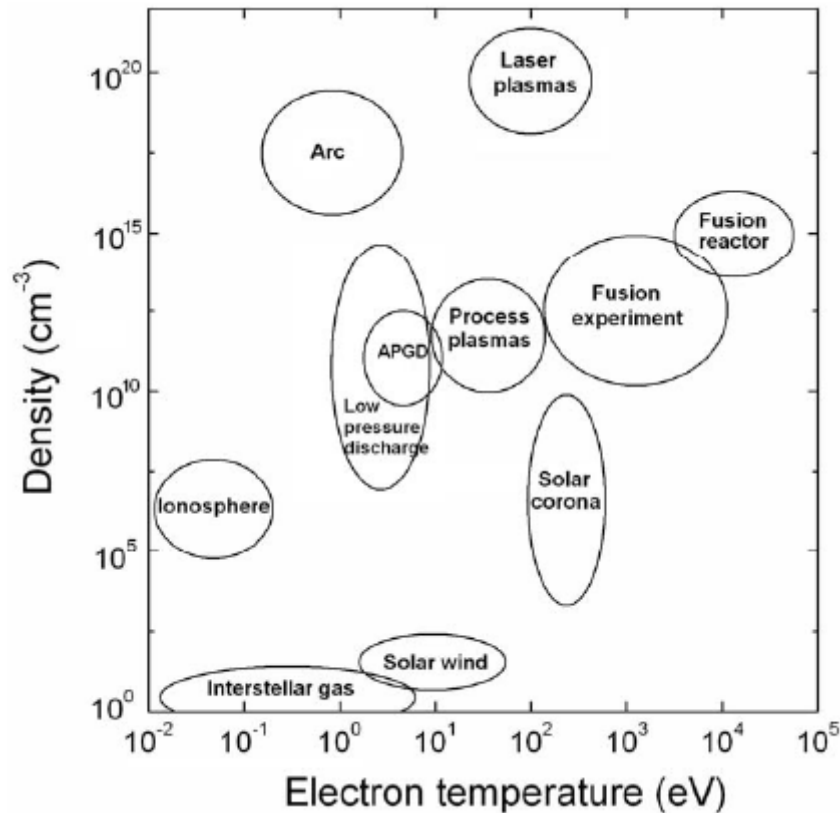


Figure 1 displays the relation between electron density and temperatures in a variety of different plasma environments (Cao 2010)

Plasmas can be classified as thermal or non-thermal plasma. Thermal plasma is when the temperature of the electrons is equal to the temperature of the neutrons. This is common where plasma is generated through heating, although thermal plasma generation is still possible using other techniques such as electromagnetic fields. That being said, although thermal plasmas have the same electron and ion temperatures, they may not have the same temperatures as the neutral species. Often thermal plasmas will also have a higher plasma density than non-thermal plasmas (Taylor and Pirzada 1994).

Plasmas such as atmospheric pressure glow discharge (APGD) are non-thermal; electron temperatures will be considerably higher than ion temperatures. They are also characterised as cold plasma as the ions in cold plasma are often much cooler than the electrons, which can reach temperatures of tens of thousands degrees. However, as the mass of electrons are likewise considerably smaller

than ions, there is a limitation to how much thermal energy may be transferred to the environment (Wiesemann, n.d.).

2.1.1 Atmospheric Plasma

The commercial applications of plasma based technology has been increasing in the recent years, from the well-known manufacturing techniques of sputtering and etching (Wilkinson and Rahman, 2004) to biological decontamination (Niemira 2012) to surface energy modification (Wolf and Sparavigna, 2010) to the cleaning of surfaces (O'Kane and Mittal 1974). The microelectronics industry heavily relies on the use of both plasma deposition and etching for micro manufacture of a thrird of components (Lieberman and Lichtenberg 2005).

Atmospheric pressure plasma is becoming increasingly popular in industry due to the removal of a vacuum from the process. This not only removes the time and expense associated from sustaining vacuum conditions, but also increases the possible range of applications (Kanazawa et al 1988). Atmospheric Plasma technology can be portable, leaving the laboratory/factory environment and entering hospitals (Freeman and Auer, 2012) or even greenhouses (Misra et al 2016).

2.2 Temperature Sensing

Temperature, whether measured in Kelvin, Celsius or Fahrenheit is often considered as a measurement of how hot, or cool a surface or environment is. Particularly we consider temperature to be related to heat, which either enters or leaves a particular environment to result in a temperature change. Blundell and Blundell (2006) define heat to be 'energy in transit', where the amount of heat within a system cannot be directly quantified. The in transit refers to the necessity of a degree of heat transfer required to measure the heat energy.

Although heat causes a rise in temperature, transfer of heat can lead to a change in matter state, i.e. melting, boiling (Rusby 2016).

Maxwell in 1866 described that the temperature of a body is regarded as a measure of its ability to transfer heat to other bodies. From this he formed his kinetic theory which stated that temperature, and heat, is simply related to molecular movement, simplifying the laws of thermodynamics.

As a form of energy, joules are used to measure heat, with watts measuring heat transfer, in joules per second. Heat capacity ($C \text{ JK}^{-1}$) is defined as the amount of heat energy ($\Delta Q \text{ J}$) that must be supplied to an object or system to achieve a small rise in its temperature, divided by the magnitude of that change ($\Delta T \text{ K}$) as described below.

$$C = \frac{\Delta Q}{\Delta T} \quad (2-5)$$

This formula can be further explored to include the specific and molar heat capacity which relates the heat capacity to a unit mass or one mole of the measured substance (Blundell and Blundell, 2006).

As temperature in gases is related to volume and pressure it is important to consider heat capacity at a fixed volume C_v and a fixed pressure C_p which may be described using partial differential equations shown below. (Blundell and Blundell, 2006)

$$C_v = \left(\frac{dQ}{dT} \right)_v, \quad C_p = \left(\frac{dQ}{dT} \right)_p \quad (2-6)$$

2.2.1 Methods of Heat Transfer

There are fundamental mechanisms for heat transfer which include conduction, advection, convection and radiation in the form of infrared (IR) photons. Conduction applies to solid bodies while convection and advection applies to the heat transfer within fluids (liquids and gases). Radiation does not require media for its transfer energy and hence may pass through a vacuum.

Although IR radiation may also pass through both solids and fluids, the surface of a substance will affect the ability of the IR wave to permeate into the body or to be reflected (Cao 2010).

2.2.2 Temperature Measurement

As energy is transferred from one object to another, time is required to ensure that the heated object has reached the same temperature as the 'cooled' object. When the thermal energy content ceases to change between the two bodies, thermal equilibrium has taken place (Blundell and Blundell, 2006).

For this reason it is important to understand the specific heat capacity of any temperature measurement sensors, to ensure an adequate amount of time has been taken for thermalisation without altering the temperature of the object (Blundell and Blundell, 2006). It is also important for the sensor's physical size to remain as small as possible so the temperature of the sensor does not affect the temperature of the measurand (Rusby 2016).

Contact is also important when measuring temperature using contact sensors. Ideal temperature measurement will include the temperature sensing element being as physically connected to the measurand as possible. Calibration should also be considered, with a check of conformity before the measurements (Rusby 2016).

2.3 Thermocouples

Thermocouples (TCs) are temperature sensors which utilise the Seebeck effect. This is where a voltage is generated within an electrical conductor, when there is a temperature difference along its length. In practice this composes of two wires, of different material, joined to form the sensing element. The other ends are connected to a voltmeter where the difference between the two voltages in each wire is measured (Morris and Langari 2016).

Thermocouples are a common temperature sensing device as they are easy to use and relatively cheap to purchase. K type thermocouples are standardised in IEC (BS EN) 60584-1 and should produce similar readings from sensor to sensor. They carry a range from -270°C up to 1200°C (Rusby 2016).

2.3.1 Thermocouples in Plasma

Thermocouples are one of the most common temperature sensing devices, so it is not unsurprising that they have been attempted to be used as a physical temperature sensor for plasma, however to little effect. Thermocouples are prone to interference from electromagnetic fields, measuring much higher/lower than they are supposed to. They also risk acting as a heat sink, lowering the temperature in their vicinity.

Van Gessel (2012) used K type thermocouples to measure the air temperature around the plasma, although stated that they do not work within the plasma area. Temperature measurements were taken 12mm away from the edge of visible plasma.

Weimer et al (1991) used quartz shielding encapsulating a TC to measure the temperature of a microwave plasma at 800°C. Shielding may overcome the effect of the electromagnetic field however it also disrupts the temperature sensing abilities by additionally shielding the heat. Not to mention, the addition of a shield creates a bulky sensor which may further disrupt the gas flow.

Amiel (2012) measured surface temperature using IR cameras and thermocouples. They found that the thermocouple reading measured lower than that of the thermal camera.

Farias et al (2017) found that interference from the RF field caused issue with the temperature measurement systematically. With shielding this was reduced to just 2°C difference. This was recorded by turning off the RF source and measuring the difference. They also showed slow reaction times, taking 2 minutes to increase the thermocouple temperature by 2°C.

Knozer et al (2012) studied the use of several temperature measurement devices under cool plasma, for food science applications. They found that TCs have long response times and read lower than phosphor fibre optic sensors.

Meng et al (n.d) speculate that error may exist in high temperature environments due to the complex heat transfer processes involved, such as the heat conduction along the thermocouple wires.

They found that about 4.5 seconds was required to achieve a steady state of temperature measurement. Large errors were present in the results including thermocouples measuring temperature much lower than with the spectral method.

2.4 Fibre Optic Sensing

An optical fibre consists of a higher refractive index core and a lower refractive index cladding, to allow for total internal reflection, resulting in a cylindrical dielectric waveguide. Usually these are made of glass or polymer (Zhang, 2012).

According to Snell's law a wave incident upon a boundary will be reflected and partially refracted. Total internal reflection occurs where the angle of the direction of the beam of light, n_i , between that of the fibre cladding is greater than the critical angle, n_c , as described below.

$$\theta_c = \sin^{-1}\left(\frac{n_c}{n_i}\right) \quad (2-7)$$

Where n_c is the refractive index of the fibre cladding while n_i is the refractive index of the fibre core (Ghosh et al 2015).

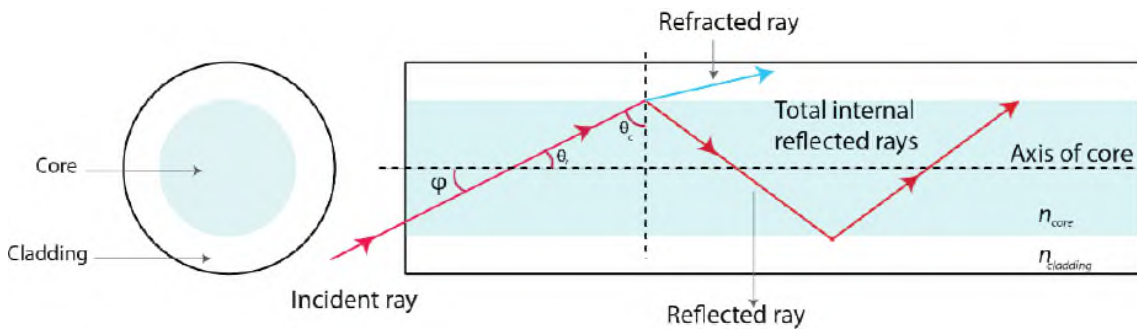


Figure 2a (left) displays a cross section of a single mode fibre consisting of a high refractive index core and lower refractive index cladding. Figure 2b (right) displays internally reflected light propagating along a fibre. (Amos, 2018)

Fibre optic sensing is a broad term for the use of any light and cable based measurement device. Which can further be classified as single mode or multi-mode (Amos, 2018). Single mode fibre is composed of a narrow core and a surrounding cladding layer. Due to the smaller diameters, light reflections are reduced and attenuation is lowered, thus allowing for further travel. Multiple mode fibre has a much larger diameter allowing for more data to transmit over time, although dispersion and attenuation increase (Ahamed 2013).

Fibre optic sensors are divided into two categories; intrinsic and extrinsic. Intrinsic sensors rely on the light remaining confined within the fibre, such as grating sensors, placing an emphasis on the material properties of the fibre. Extrinsic sensors have the light leave the fibre, interact with a sensing element, before returning back to the fibre.

Several factors, such as intensity, phase, wavelength and polarisation affect the propagation of light through a fibre. Each of these parameters can be exploited as a different sensing technique, allowing for a wide array of measurement pathways. Fibre optic sensors can be categorised into one of four types of modulation; Intensity, phase (interferometric), spectral (wavelength) and polarisation (Amos, 2018) (Güemes and Messervey 2010) (Suresh et al 2012).

Intensity modulation sensing measures any qualities which could affect the optical power. Light is passed through a fibre towards a transducer which alters the intensity before the signal returns to the detector (Medlock 1987).

Phase modulation sensors rely on interferometry, the observation of constructive interference between two light beams, resulting in a change of the cavity length of one of the interference arms (Amos, 2018) (Slepukhov 2018).

Spectral modulation involves the measurement of a change in wavelength depending on a change in certain physical parameters. Grating sensors are the most commonly used special modulators, where pressure, strain and temperature affect the reflected, or transmitted wavelengths (Arie *et al* 1999) (Güemes and Messervey 2010) (Rogers 1977).

Polarisation modulation is based on one of two effects; The Faraday's effect or the Photo-elastic effect.

In 1845 Michael Faraday discovered the optical phenomenon of Faraday rotation involving the polarisation of an electromagnetic wave in a magnetic field. When a magnetic field is applied parallel to the optical fibre, the polarisation plane is rotates at an angle (θ) proportional to the magnetic field (B) and the thickness of the fibre core (d) as shown below (Miura 2011)

$$\theta F = VBd \quad (2-8)$$

Where v is the Verdet constant, a function itself of light and wavelength. Due to this polarisation, these sensors are capable of measuring electric and magnetic fields (Miura 2011).

Discovered as fibre sensing technique by Spillman (1982), the photo elastic effect describes changes in optical properties of the fibre when subjected to mechanical stress. These fibres are designed so that pressure will affect the polarisation of the fibre itself. (Amos, 2018) (Mindlin 1939) (Wang *et al* 1992)

2.4.1 History of Fibre Optic Sensors

In 1976, Vali and Shorthill tested the use of a fibre ring interferometer gyroscope for navigation, showing that has the sensitivity to be effective, detecting low angular velocities. Rojers, A, (1977) demonstrated the use of optical methods to measure current and voltages in power systems. For temperature the first fibre optic sensors were often open air path sensors, modified to incorporate optical fibre, however since then fibre optic sensors have been developed in their own right. (Grattan, K., 1995).

Soon after, the first light and phase modulation based fibre sensors were developed such as those by Giallorenzi *et al* (1982) and Mellberg (1983) respectfully. Such sensors were susceptible to changes in the intensity of light received by the detector, which may have been caused due to scatter, absorption or bending losses. Intensity fluctuations and loss at connectors also play a part in affecting the results. This could be overcome by time averaging to record the spatial changes in scattering or loss, however increasing the induced noise in the process (Suresh *et al* 2012).

In 1978 Hill *et al* formed periodic perturbation reflection filters through the exposure of a photosensitive germanosilicate optical fibre core to propagating coherent beams resulting in a standing wave pattern. Several grating writing techniques were subsequently developed including that of Hill *et al* (1993) which utilised a phase mask technique, forming an interference pattern in the +/- 1 order

(Suresh *et al* 2012). This results in the fibre containing a wavelength modulation, or Bragg grating, removing the aforementioned disturbances from signal losses.

2.4.2 Applications and advantages of fibre optic sensing

Fibre optic sensors have a wide array of benefits such as their ability to withstand harsh environments, light weight and thin size which makes them easy to apply in a wide array of applications such as the oil and gas industry. They are a relatively safe and non-toxic sensing option which allows for promising use in the medical device sector (Amos 2018) (Ulises, 2018).

Other benefits include immunity to electromagnetic interference coupled with high accuracy (Suresh *et al* 2012). They also have the benefit of being able to transmit signal across a wide area without loss of information (Amos 2018). Fibre optic sensing is used for the measurement of fuel in the aerospace sector due to the non-conductive and chemically inert nature of glass fibre. The wide bandwidth and multiplexing abilities of fibre Bragg gratings further increase their applications, (Lee, 2003) from biochemical systems (Liu, 2019) to the detection of changes in potential difference, through bonding with piezoelectric Lead Zirconate Titanate, for use in protection systems (Rami, 2016).

2.5 Fibre Bragg Gratings

Fibre Bragg gratings are based on the principle of Bragg reflection (Ghosh *et al* 2015). As mentioned in 2.4.1, Bragg gratings are periodic refractive index changes, propagating along the core (Liu, 2018), causing a partial mirror where specific wavelengths will be reflected while others will pass through. (Ghosh *et al* 2015).

Fibre gratings moderate optical diffraction affecting the light wave incident. The effect of the incident angle (θ_1) has on the diffraction angle (θ_2) at a given wavelength (λ), grating period (Λ) and refractive index is described below.

$$n \sin \theta_2 = n \sin \theta_1 + m \left(\frac{\lambda}{\Lambda} \right) \quad (2-9)$$

Where m is the order of Bragg diffraction.

Light reflected through a fibre by a Bragg grating has a wavelength (λ_b) which corresponds to twice effective refractive index (n_{eff}) multiplied by the grating period (Λ), known as the Bragg condition (Kersey et al., 1997), as shown below (Suresh et al 2012).

$$\lambda_b = 2n_{eff}\Lambda \quad (2-10)$$

When a beam of light passes across the alternating periods of high and low refractive index, there is partial reflection at each period. If the length of the period allows, the partial reflections will add up in phase, increasing the total reflection considerably. All other reflections will be out of phase, cancelling each other out and transmitting along the rest of the fibre (Ghosh et al 2015).

$$K = \beta_F - (-\beta_R) = \frac{2\pi}{\Lambda} = 2 \frac{2\pi}{\Lambda_B} N_{eff} \quad (2-11)$$

The above equation describes the coupling of the forward (propagation constant, β_F) and reflecting light beams (propagation constant, β_R), where the Bragg condition is satisfied. Here the special frequency of the grating is equal to the propagation coefficient (K) of the coupled modes. The equation further describes which wavelengths will provide intense reflection.

Fibre Bragg grating sensors are often classified into two types; one being Bragg gratings, also known as 'short' or 'reflection' gratings, where coupling occurs between waves traveling in opposite directions. The other is known as Long Period gratings, or transmission gratings where the coupling occurs in the same direction. (Cusano et al 2019) (Ghosh et al 2015)(Suresh et al 2012). Within this thesis, we will be focusing on the former reflection gratings, measuring their wavelength change in reflection across a temperature change.

The wavelength that is returned, also known as the Bragg wavelength, thus will change when either the refractive index, or the period length changes. This

means that the FBGSs are affected by the temperature, pressure and strain acting upon them (Suresh et al 2012), thus making is ideal for temperature sensing (Khan 2012).

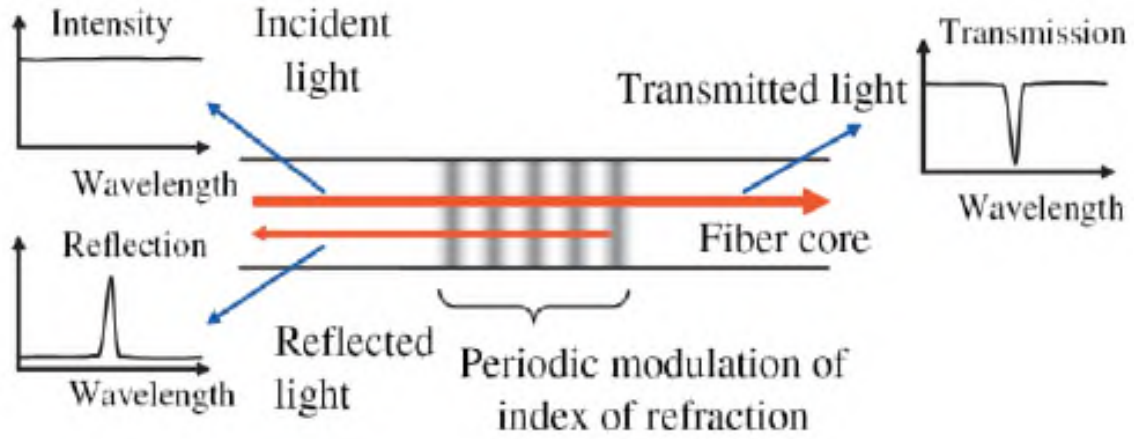


Figure 3 displaying a fibre Bragg grating within a fibre core (Cusano et al 2019).

In theory, an infinite amount of Bragg wavelengths could exist within a single fibre, at varying wavelengths. The limiting factor in practice is dependent on the fibre material properties or the light source spectra range, which often does not exceed 100nm (Khan and Ahmed 2012).

When the grating period is uniform throughout the sensor, some wavelengths other than the Bragg wavelength are reflected although this is at much lower intensities. These side lobes can be reduced by having an apodised sensor, a sensor where the grating period is slightly smaller at either side of the sensor (Güemes and Messervey 2010) (Ghosh et al 2015).

For a temperature change (ΔT), the shift in wavelength ($\Delta \lambda_B$) can be calculated by multiplying the change in temperature by the original refractive index ($\Delta \lambda_b$) and the sum of the coefficient of thermal expansion (α) and the fibre thermo optic coefficient (ξ) as shown below (Hirayama and Sano 2000) (Othonos and Kalli 1999).

$$\Delta \lambda_B = \Delta \lambda_b (\alpha + \xi_T) \Delta T \quad (2-12)$$

It is important to note that not only is temperature measured in a FBGS, but also strain (ϵ). In this case, the effect of strain may be added to the effect of temperature as shown below (Othonos and Kalli 1999).

$$\frac{\Delta\lambda_B}{\Delta\lambda_b} = K_T\Delta T + K_\epsilon\Delta\epsilon \quad (2-13)$$

Here the change in strain is multiplied by the strain effect (K_ϵ) while temperature is multiplied by the FBGS temperature sensitivity (K_T) (Othonos and Kalli 1999).

3 Methodology

The viability of using FBG sensor to measure temperature for a microwave atmospheric pressure streamer plasma jet was considered. As a comparison, thermocouple was also used. Fibre Bragg gratings were then used to characterise the temperature profiles of the jet, and fluctuations of temperature over time. Fibre Bragg gratings were further used to explore the temperature profile of a radio wave frequency atmospheric plasma jet.

Thermocouples are currently used to compare temperature measurement of the FBGS to another physical sensor as they are currently used for low temperature measurements of plasma as mentioned in section 2.3.1.

K type thermocouples consisting of class 1 wire with a 0.25mm diameter (overall 0.9 x 1.3 mm) wire gauge and glass braid insulation, rated up to 480oC, were purchased from Omega Engineering inc.

Glass apodised Fibre Bragg grating sensors were purchased from Laser 2000. Fibre was polyimide coated around the sensor region but not coated over the sensor. Fibre core diameter was 10µm while the sensor region was 600µm. The grating period was 1070.99 nm.

$$2n_{eff} = \frac{\lambda_b}{\Lambda} \quad (3-1)$$

$$2n_{eff} = \frac{1549.44nm}{1070.99 \text{ nm}}$$

$$n_{eff} = \frac{1.446736197350115}{2}$$

Taking into consideration equation (2-10), and the Bragg wavelength of 1549.44nm at 25°C we can calculate the effective refractive index, as shown above, to be 0.723 (to 3 s.f.).

Argon gas was used to produce plasma from a PM01 ‘mini torch’ produced by Adtec Europe Ltd. This is a microwave power non-thermal system capable of

producing plasma jets with a full width half maximum of 2mm. The plasma gas temperatures are estimated by the company specifications as being between 30 to 200°C at a 20mm distance from the torch head. The torch produces negligible UV and is intended to be at a temperature which is low enough not to burn skin. Gas flow can be altered from 0.5 to 5 Lmin⁻¹. The electric power has a maximum of 15w, with a fixed 2.35 GHz frequency. The ignition system is a manual push pin style.

Initial trial experiments involving the plasma torch and it's capability with thermocouples involved positioning the torch horizontally, at a set distance from the thermocouple. The torch was subsequently integrated into to the RAPT 300 machinery, mounting it vertically so that the plasma jet sprayed downwards as shown in Figure 4.

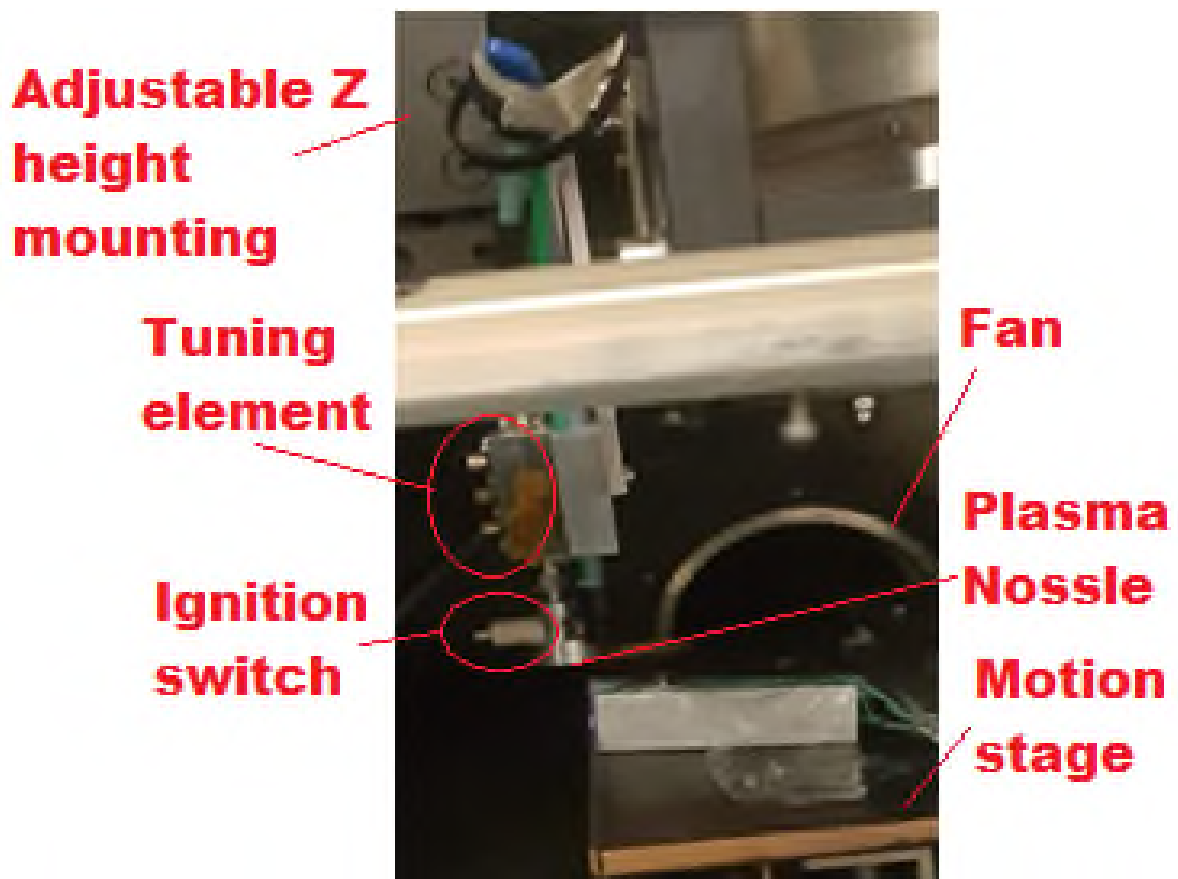


Figure 4 shows the Plasma Tact vertically mounted into the RAPT300 machinery.

Higher temperature radio frequency plasma was produced from a RAPT300 prototype torch produced by RAP industries, installed at Cranfield University in 2005. RAP stands for Reactive Atom Plasma, a chemical etching process which combines an inductively coupled argon plasma with a chemically reactive gas injected into the centre. In this case, only the argon plasma will be produced without any reactive species, reducing the concern of the plasma reacting with the Fibre Bragg grating sensor (FBGS). There was also an increase in nozzle to sensor distance where the z height in this case was increased to 10cm, to ensure temperatures would not exceed 1000°C.

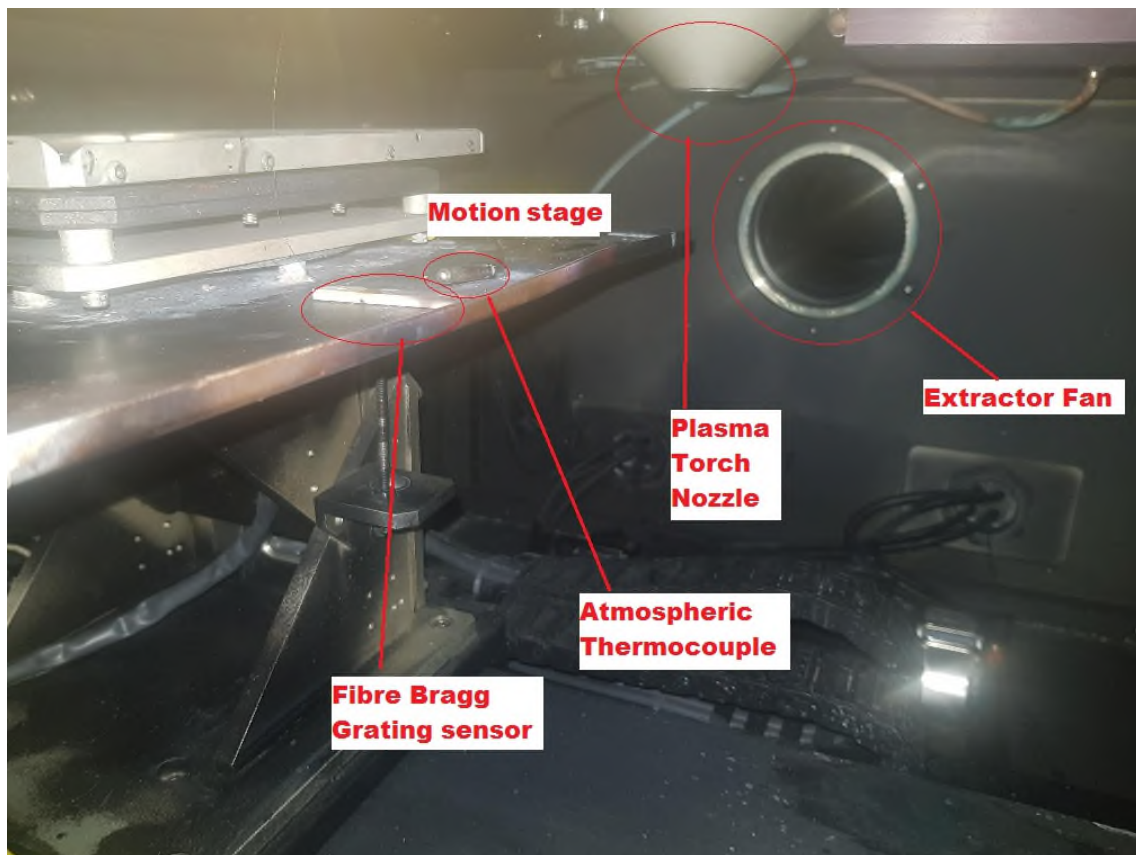


Figure 5 shows the setup of the RF temperature measurement experiments. The RAPT300 in built thermocouple was used to measure the air temperature around the plasma.

Initial experiments using FBGS involved mounting the sensor onto thin sheets of Polyvinyl chloride (PVC) or Silicone. PVC proved to be thermally unstable while silicone was deemed too brittle and risked sensor breakage. PVC substrate was

also mechanically too ductile and resulted in strain effects upon the FBGS as shown in Figure 37.

A substrate was designed to be rigid enough to ensure the safety of the jet, while also interacting less with the plasma torch. Tufnol, PTFE and MACOR were chosen to be used with the Microwave (MW) and Radiowave (RF) torches respectively.



Figure 6 displaying the effect of cool microwave plasma at 15W and 5Lmin flow rate on Tufnol.

Tufnol is made from a phenol formaldehyde resin. It was chosen due to its suitable thermal and electric properties (Tufnol.com, 2009). However initial experiments showed the substrate to appear burnt post experiment, see Figure 6. Due to this, Tufnol was not used further.

Borosilicate glass was considered but would create issues with machinability and may be too delicate. PTFE and MACOR were subsequently used due to being non-brittle but also rigid enough not to cause movement.



Figure 7 displaying the PTFE substrate with fibre Bragg grating sensor attached. One 0.3mm wide groove was milled into the substrate at a depth of 0.25mm.

PTFE has advantages due to its chemically inert nature and ability to withstand working temperatures of 260°C, with a melting temperature of 335°C. (Polyak, 2008) Additionally it has a high dielectric strength and low dissipation factor, making it suitable for cool plasma environments.

MACOR is an easy to machine glass ceramic produced by Corning Inc. It is composed of 45% borosilicate glass, with 55% fluorphlogopite mica offering similar properties to the FBGS but with enhanced strength and versatility. It has a low thermal conductivity of just 1,46 W/m°C coupled with a high dielectric strength. (Corning, 2012) Image of the macor substrate shown in Figure 8.

0.3mm wide grooves were milled into each substrate at a depth of 0.25mm. This was to contain and house the FBGS without over restraint but to ensure movement of the sensor is limited, so it does not move during measurement.

The MACOR sensor further included a second parallel groove such that there were two grooves 1mm apart in order to allow simultaneous measurement of two FBGSs. A hole was included within the substrate to measure the effect of a sensor that was partially unrestrained.



Figure 8 displays the MACOR substrate with two FBGS attached. Two 0.3mm wide grooves were milled into the substrate at a depth of 0.25mm.

Due to the strong flow rate, and the second sensor being melted due to the high temperature of the RF torch, the fibre was moved so the sensing element was in

contact with the MACOR. Subsequently only 1 FBGS was used in the measurement of the RF thermal plasma.

A moving stage has been used to control the movement of the sensors across the jet. The RAPT300 motion stage was programmed to move the substrate and sensor under the plasma at set processing speed. The location of the stage can be controlled by manually moving the stage in the x or y direction in manual increments. Alternatively the stage can be programmed to move in 'X' and 'Y' using G code.

Z heights can be controlled one of two ways. For the microwave torch, a micrometre screw is attached to the mounting of torch itself, allowing for adjustments to the height by raising or lowering the torch. The mounting has been further modified to allow the torch to be attached at higher or lower positions, further improving the range of Z heights beyond the limits of the micrometre.

Secondly a micrometre screw is also attached to the motion stage, allowing for the stage height to be adjusted for use with both the microwave and the radiofrequency torch. As a result, z heights from 0mm to 110mms have been explored.

3.1 Materials and Equipment

3.1.1 Materials

- 5L Argon Gas
- 0.6mm x 0.01mm length Fibre Bragg Grating sensor purchased from Laser 2000. (Bragg Wavelength 1549.44 at 25°C)
- 1mm x 0.01 length Fibre Bragg Grating sensor purchased from Laser 2000 (Bragg Wavelength 1550 at 25°C)
- 0.5mm x 0.5mm K type Thermocouples purchased from TC direct.
- Mercury Thermometer
- PTFE
- MACOR ® purchased from Corning Inc
- Deionised water for calibration

3.1.2 Equipment

- RAPT300 precision motion Stage purchased from RAP industries
- Plasma Tact microwave plasma torch purchased from Adtec Europe.
- RAPT300 inductively coupled plasma torch
- Optical/Light Microscope purchased from Leica Microsystems
- Talysurf CCI 6000 Coherence scanning interferometer purchased from Taylor Hobson Precision
- Hot Plate, beakers for calibration

3.2 Methods

3.2.1 Calibration

Fibres and Thermocouples were recalibrated using a range of temperatures including; 0°C, 20°C, 25°C (In the case of FBGS), 100°C, 200°C and 300°C.

Experiments between 0°C to 100°C were taken in a temperature controlled laboratory of 20(±) °C. Room temperature was assumed to be 20°C and atmospheric temperature thermometer readings was recorded to ensure temperature was not above or below this by more than 1°C. Ice water was used to ensure 0°C.

Experiments between 20°C and 300°C were further conducted in a calibration oven.

A temperature controllable hot plate located within the RAPT300 machine system was used to further ensure the temperature of the FBGS at 300°C.

3.2.1.1 Calibration of Thermocouples

Although the Thermocouples should have been purchased with their own calibration, to a high standard, the thermocouples were checked to ensure no drifts in the readings occurred.

3.2.1.1.1 Boiling Water

Thermocouples were placed in water allowed to boil on a heat plate. TC were given 3 minutes to reach boiling temperature before reading. The cold junction reading began at 20.68°C, raising to 20.78°C over time. As this is relatively stable, it is not included in the graph. Each channel represents a separate TC. Channel 4 read consistently lower than the other values and it was confirmed it would be unsuitable for use in future experiments.

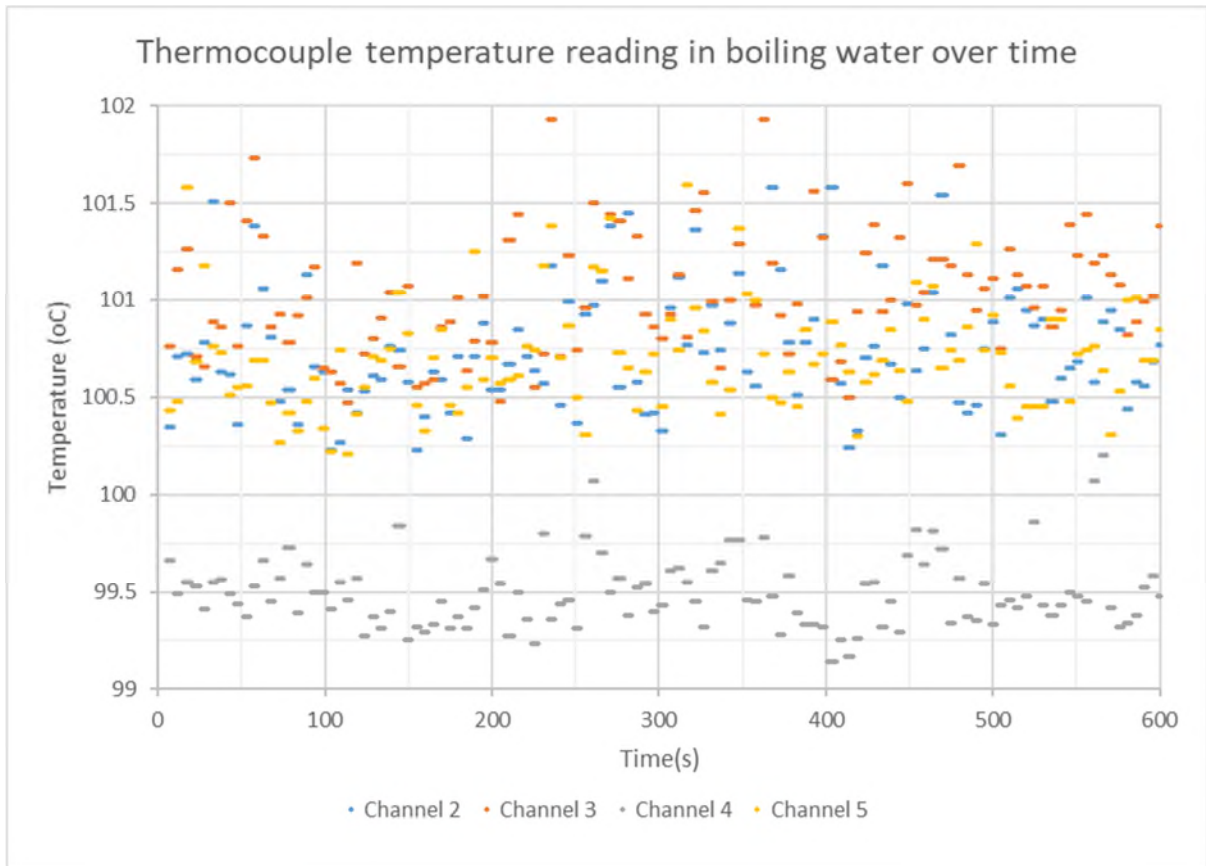


Figure 9 showing the temperature readings of 4 thermocouples over time. TCs were placed in boiling water for 1500 seconds. Note the temperature scale does not start at zero.

The standard deviation and average were taken from the temperature measurements. Thermocouple 5 was shown to have the lowest average, and the second lowest standard deviation among the other 3.

Experiments with the calibration oven confirmed the thermocouples were accurately reading $100^{\circ}\text{C} \pm 1^{\circ}\text{C}$.

Table 1 displays the average temperature of 4 thermocouples used to measure boiling water.

	Channel 2 (°C)	Channel 3 (°C)	Channel 4 (°C)	Channel 5 (°C)
Average	100.74	101.04	99.52	100.71
Standard Deviation	0.31	0.29	0.17	0.27

3.2.1.1.2 Room Temperature

Room temperature was measured to be between 19.8°C to 21°C according to the laboratory atmospheric temperature thermometers. The TC in built cold junction set the temperature to be starting at 21.17°C, lowering to 20.92°C over the 10 minutes.

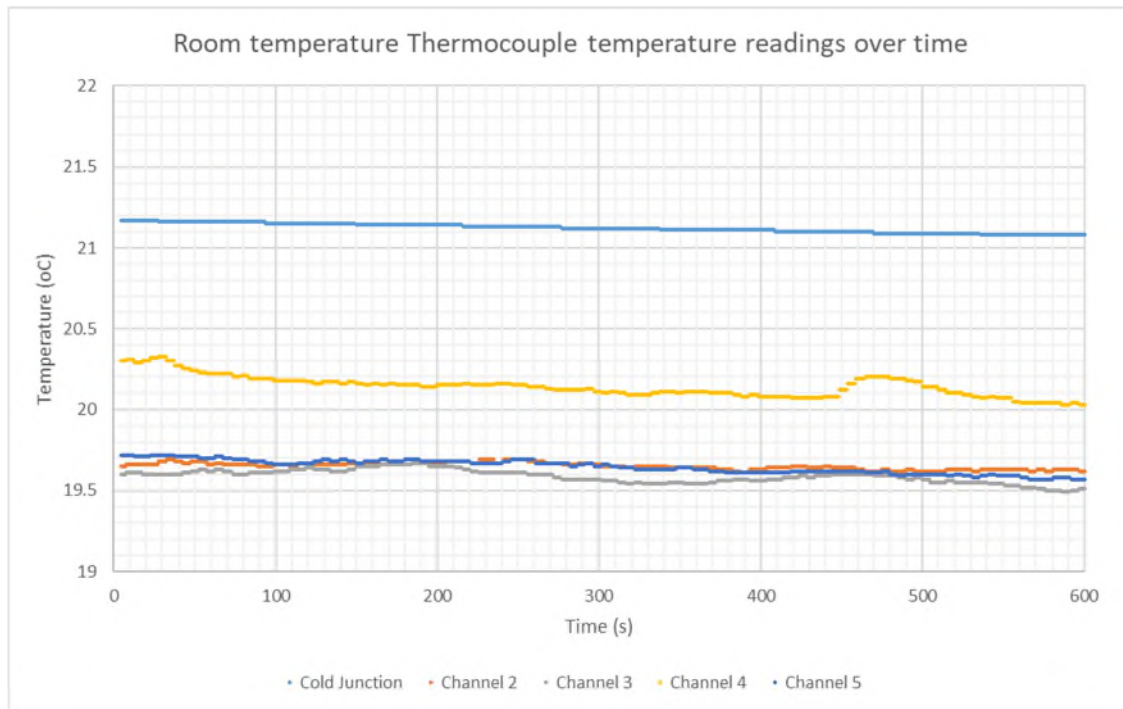


Figure 10 showing the temperature readings of 4 thermocouples over time. TCs were kept at room temperature for 1500 seconds. Note the temperature scale does not start at zero, and has a temperature range from 19°C to 22°C.

As shown in the above graph thermocouple 2 and 4 showed some temperature instability that did not seem to match the temperature of the cold junction or the other two sensors. Due to this, TC 2 and 4 have been excluded from future experiments.

The data showed that the thermocouples may be reading too high at high temperatures by 1.5°C and too low at room temperature by the same amount. The discrepancies in room temperature could be due to the variation of room temperature across the lab. The boiling water results could be affected by the flow of the water within the beaker. From this experiment we can conclude that

the TCs are accurate to $\pm 2^{\circ}\text{C}$. Thermocouple 5 was chosen for future experiments due to its stability and consistency.

3.2.1.1.3 Triple Point of Water

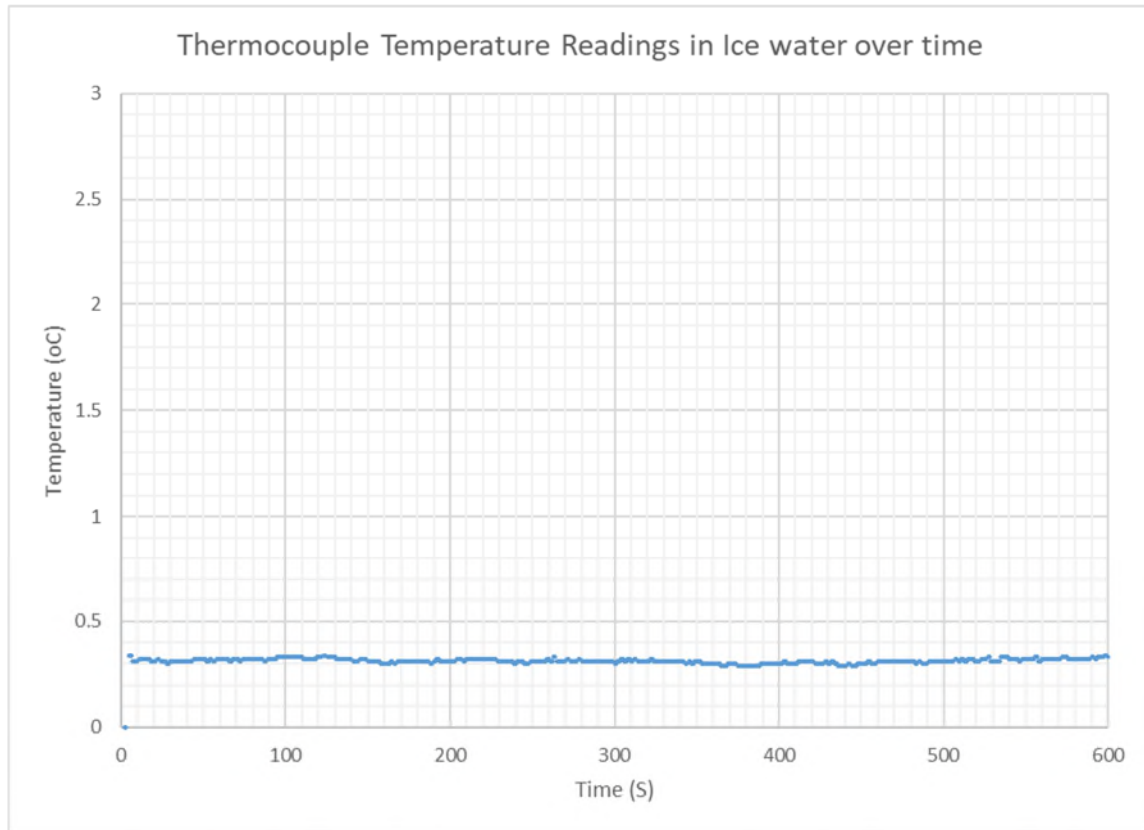


Figure 11 shows the temperature reading of TC5 in ice water over 150 seconds. The reading shows an average temperature of 0.32°C with a standard deviation of 0.0648.

Thermocouple 5 was chosen for future experiments to compare the results of thermocouple readings against fibre Bragg grating readings.

3.2.1.2 Calibration of Fibre Bragg Grating Sensors

Conventional calibration methods apply a scale factor of around $10\text{pm}/^{\circ}\text{C}$ to temperature calculations with sensors. (Chen et al., 2018)

However, the fibres were still checked using the same methods as 3.2.1 but with the added bonus of being able to acquire the Bragg wavelength at 25°C from the supplier's transmission and reflection report.

The report stated a reflection wavelength of 1549.44nm with a transmission wavelength of 1549.43. The reflection bandwidth was 0.87nm with a full width half maximum of 0.9nm and a reflectivity of 29.368%.

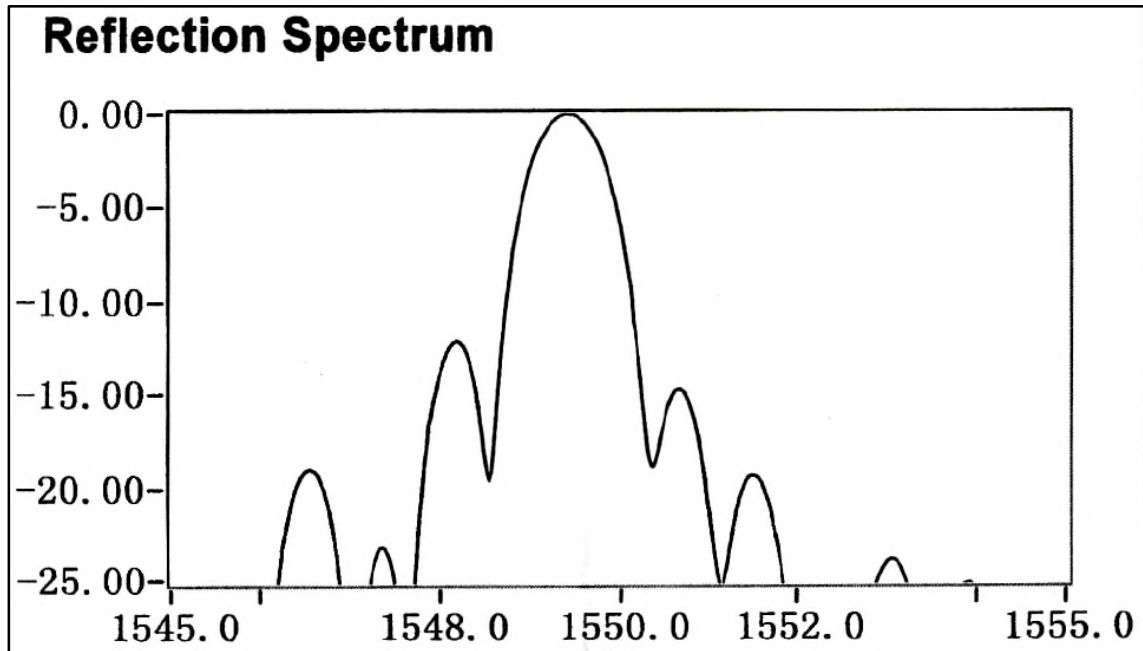


Figure 12 Reflection Spectrum of Fibre Bragg grating Sensor A at 25°C

3.2.1.2.1 Laboratory Calibration

The calibration methods as stated in section 3.2.1.1 were also applied to the FBGS. The average wavelengths at 0, 20 and 100°C were used to calculate the scale factor to be used in the conversion of wavelength to temperature.

Table 2 describes the average wavelengths recorded using a FBGS at various conditions; Ice water, room temperature, boiling water

Temperature (°C)	Average wavelength (nm)
0	1549.166
20	1549.372
100	1550.155

Using equation (3-2), the scale factors were calculated between 0 to 20°C, 20 to 100°C and 0 to 100°C.

$$K = \frac{\Delta\lambda B}{\Delta T} \quad (3-2)$$

Table 3 describes the scale factors (to 3.s.f) calculated where $\Delta\lambda B$ is calculated using the average wavelengths at two different temperatures.

Temperature Range (°C)	Scale Factor (pm)
0 - 20	10.3
20 - 100	9.99
0 - 100	9.89

The results show the calculated scale factors range from 9.89 to 10.3pm. Given that 10pm is the standard scale factor for FBGS, it was chosen to be used during calibration over and hot plate experiments up to 200°C.

Calibration oven experiments showed that the scale factor was appropriate for 200°C. As the sensor broke during calibration, we are unable to fully understand the effect of the scale factor above 200°C. A separate FBGS was calibrated with the same period and core diameter, only with a centre reflected Bragg wavelength of exactly 1550nm at 25°C. This sensor was not used for microwave plasma experiments as the sensor length was 1mm, which was deemed to be too long for a 2mm wide jet.

Evaluating the scale factor between, using data from the oven and the hot plate between 20°C and 300°C showed the scale factor to be 11.074pm for the 1mm length fibre. It is this scale factor which was applied linearly for RF experiments.

3.2.2 Mercury Thermometer

Temperature of TC was compared against a standard mercury thermometer with an accuracy of $\pm 1^\circ\text{C}$ and a range of 0°C to 100°C . This was conducted to provide a 'rough estimate' of the temperature of the jet, particularly at different z heights. As the Plasma Tact torch was designed to be cool enough to touch without burning oneself, it was expected that the thermometer would read temperatures of about 50°C .

Table 4 displays the temperature reading of a mercury thermometer at varying Z heights.

Z (mm)	Temperature ($^\circ\text{C}$)
0	78
5	59
10	49

The temperature at various Z heights is displayed above. At 0mm z height from the tip of the thermometer the reading was found to be 78C. Considering the large diameter of the mercury thermometer (4.68mm) compared with the small jet size of the torch (2mm) and even smaller diameter of the TC (0.5mm), it should be assumed that the mercury thermometer (MC) is also taking into consideration the temperature of the air around the jet which may be considerably cooler. It should also be noted that the MC is reading for temperatures of a wider array of z heights. The 0z height reading would be more indicative of the temperature in between 0 to 4.68mm Z. Nether the less it does provide some indications on the accuracy of the TC, once the data is analysed.

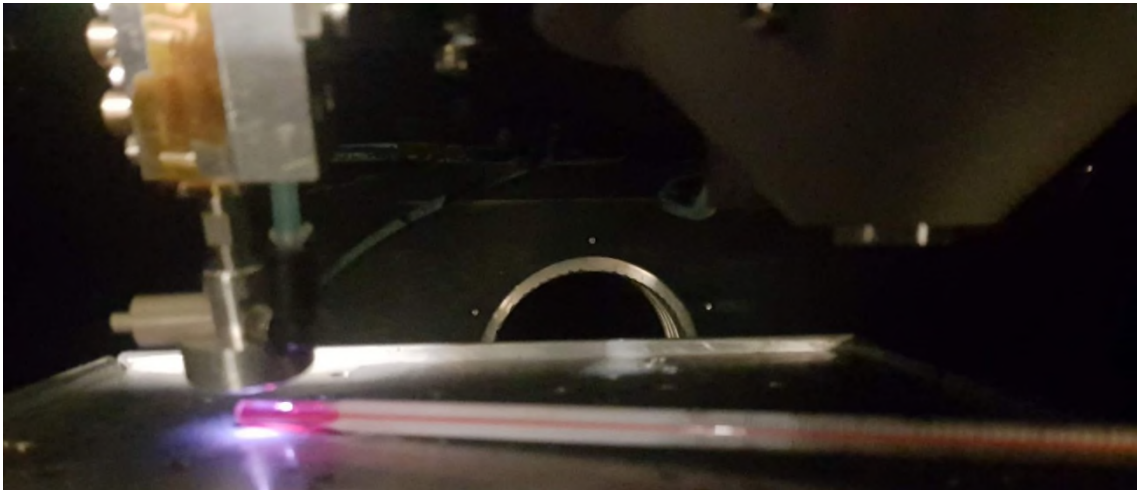


Figure 13 displaying temperature measurement taken by a mercury thermometer.

3.3 Experimental Methods

The experiment conducted has two major directions. The first is to evaluate the use of FBGS as a physical probe in non-thermal plasma. The second is to use FBGS to outline the temperature of both thermal and non-thermal plasma at various positions within the jet in order to build temperature profiles of each jet.



Figure 14 displaying the Plasma tact emitting a non-thermal microwave plasma jet

The use of FBGS and TCs were evaluated in MW plasma at a variety of different parameters including flow rate, power, and z heights. The response times of the sensors was also observed under plasma. Microscopy was used to ensure no damage occurred to the FBGS.

Aside from calibration, the FBGS were tested at room temperature across various flow rates and conditions to rule out effects on the temperature reading from mechanical strain.

The FBGS was then used to characterise the temperature profile of MW plasma across the x and y axis of the cross section of the jet. TC was used to compare an existing physical temperature measurement device to the sensor.

RF plasma was further evaluated to measure the temperature distribution of the thermal plasma as obtained from the previous method.

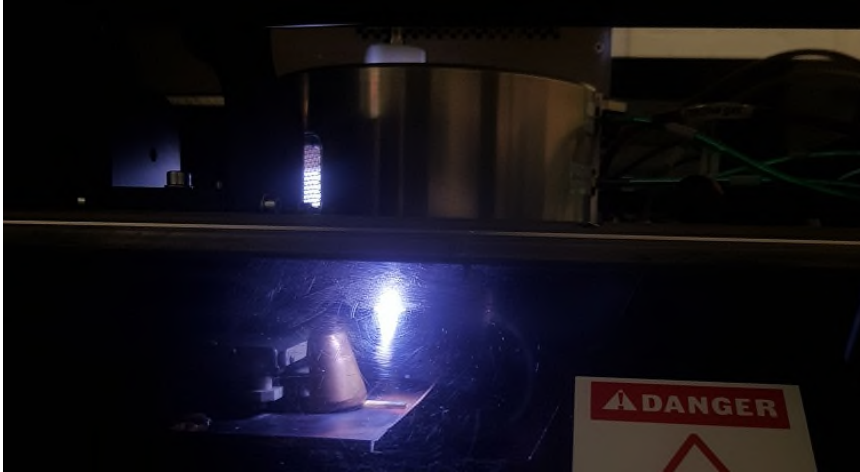


Figure 15 displaying the FR torch emitting a plasma jet upon the FBGS

4 Results

4.1 Non-Plasma Temperature Measurement

The FBGS was tested in similar to test conditions, but without igniting the plasma. Initially, an experiment was further conducted to test the flow rate on the reading of the FBGS. This was conducted both with and without the extractor fan.

Secondly, the FBGS was tested at room temperature, with just the influence from the fan. Secondly, the movement of the table was introduced, running at the same position speed of 0.5mm per minute, as used in section 4.7. Argon gas was then run through the torch without plasma ignition. The temperature recorded from the FBGS was also observed.

4.1.1 Static Strain-induced Measurements

Temperature measurements were taken with a static FBGS to observe the effect of argon gas flow on the temperature sensing effect of induced strain. As an extractor fan is also running in the experiments, the experiment will be repeated with the external factor of the fan.

The result show that the presence of the fan made negligible effects towards the reading of the FBGS at room temperature.

4.1.1.1 Without Extractor Fan

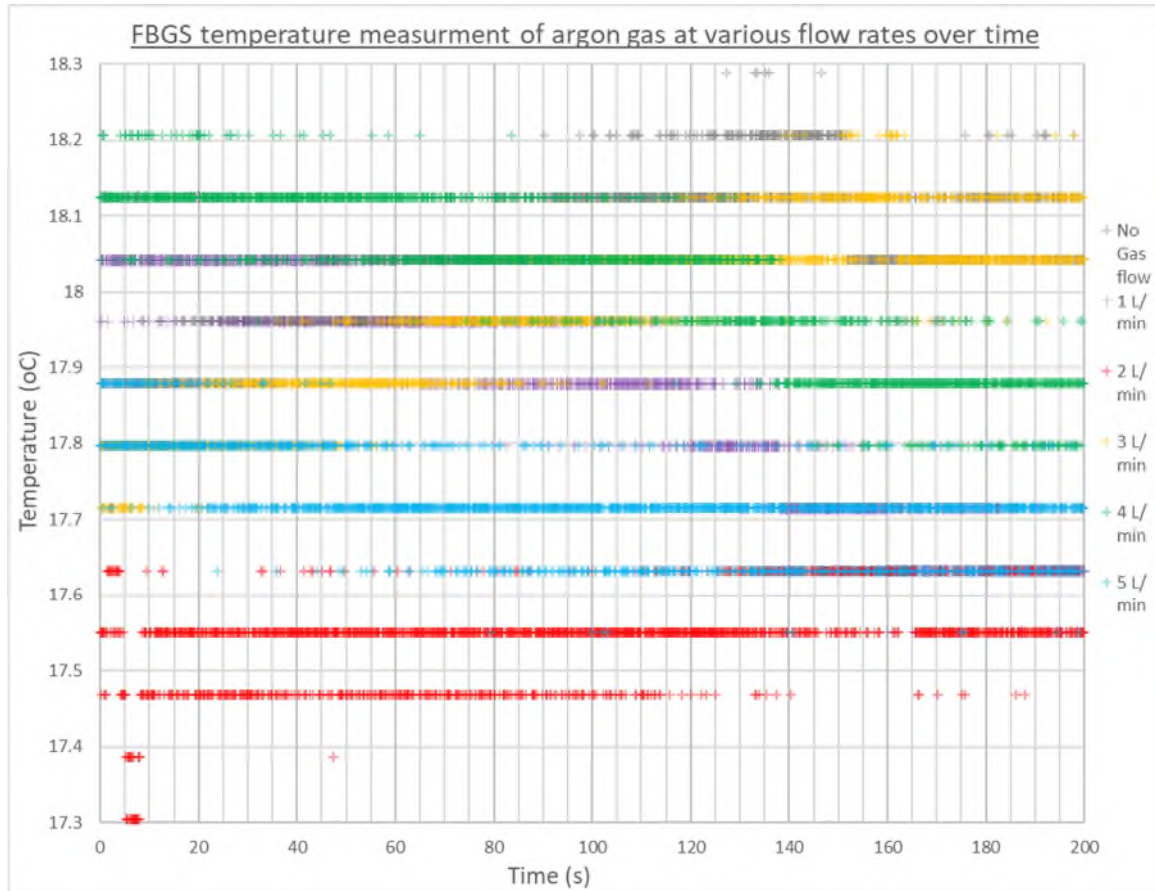


Figure 16 FBGS temperature measurement of room temperature argon gas, at varying flow rates. Results were taken over a 200 second time frame and at 10 measurements per second. Note that the variation between temperatures is less than 1°C.

Table 5 showing the temperature readings of the 0.6mm length FBGS under an argon flow at various flow rates. Results do not seem to show a correlation between gas flow rate and recorded gas temperature.

Flow Rate	No Gas flow	1 L/min	2 L/min	3 L/min	4 L/min	5 L/min
Average Temperature	18.044	17.862	17.552	17.971	18.012	17.718

4.1.1.2 With Extractor fan

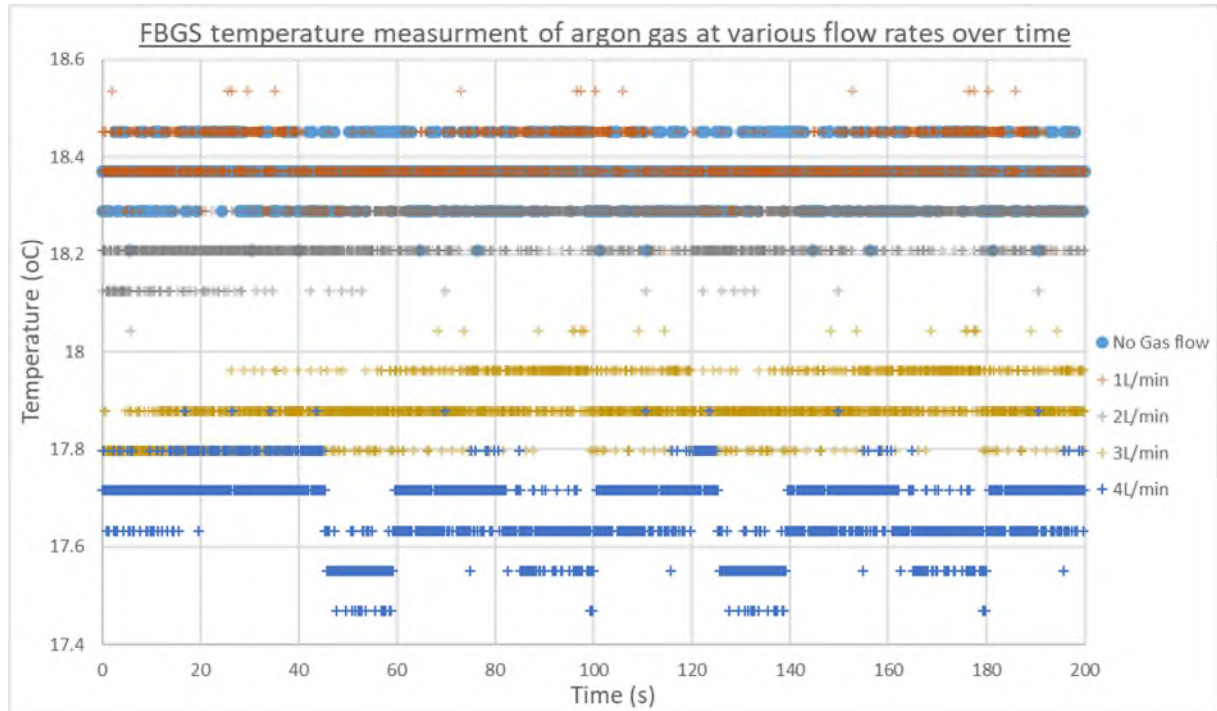


Figure 17 Experiments show that higher flow rates slightly lower the temperature reading at room temperature conditions, with the presence of an extractor fan.

Table 6 the average temperature reading from the FBGS of pure argon gas at multiple flow rates, in the presence of an extractor fan.

Flow Rate	No Gas flow	1L/min	2L/min	3L/min	4L/min
Average Temperature	18.369	18.384	18.246	17.875	17.680

4.1.1.3 Room pressure, Extractor fan and argon gas flow comparison

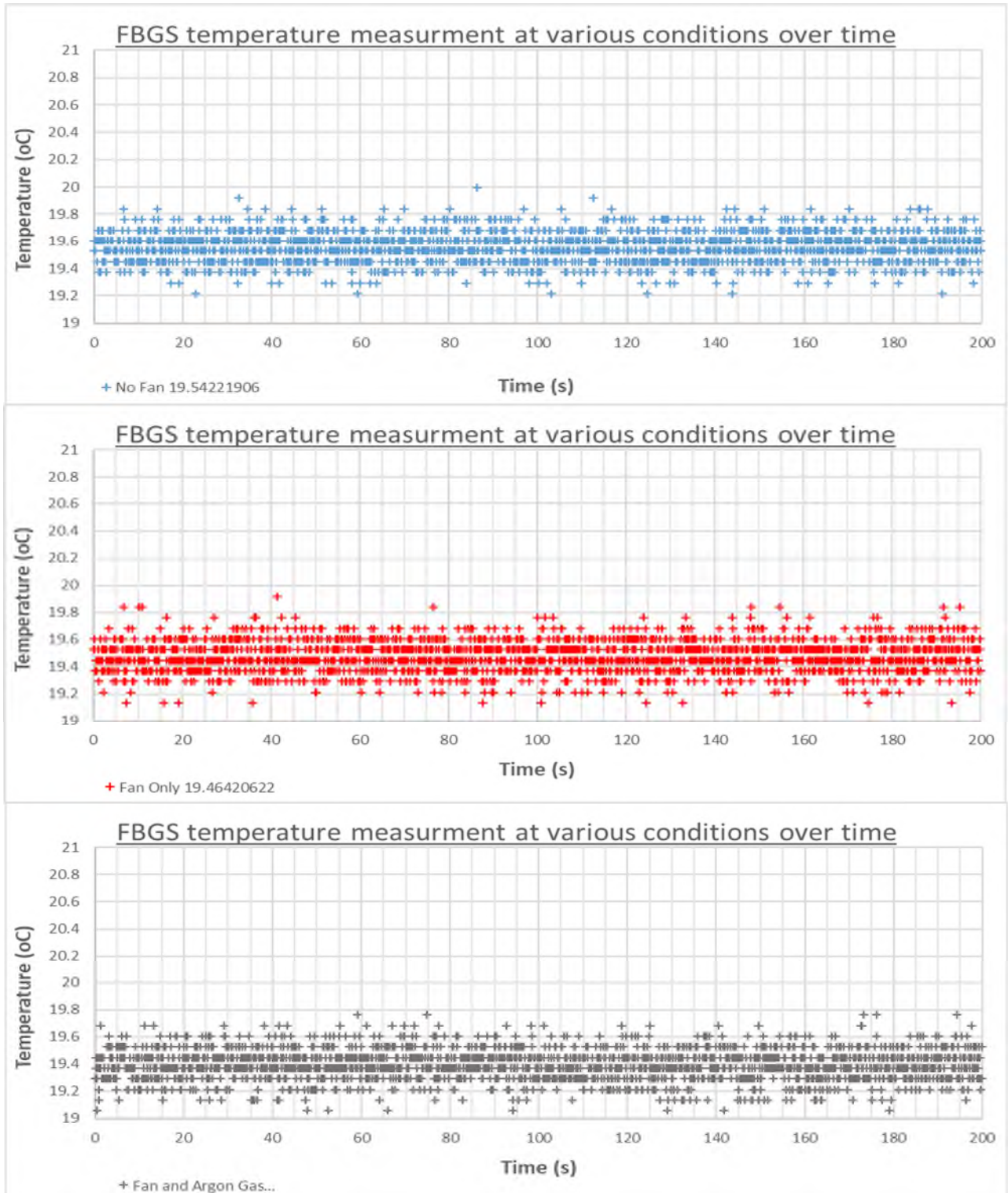


Figure 18 displaying the difference between FBGS measurement in ambient air with and without effect of the extractor fan. These measurements were compared with measurements of ambient temperature argon gas in the center of gas flow diameter at 5L/min over time.

Table 7 displays the average temperature of the FBGS measurement in ambient air with and without effect of the extractor fan, as well as ambient temperature argon gas in the center of gas flow diameter at 5L/min over time. Results show that there may be a slight increase in temperature measurement under a flow rate, although the difference in temperature is too small to be significant.

Flow Rate	No Fan	Fan Only	Fan and Argon Gas (5L/min)
Average Temperature	19.542	19.464	19.611

Figure 18 shows the use of an extractor fan alone has very little influence to static measurements, which may be seen clearer in Appendix C.

4.2 Dynamic strain induced measurement

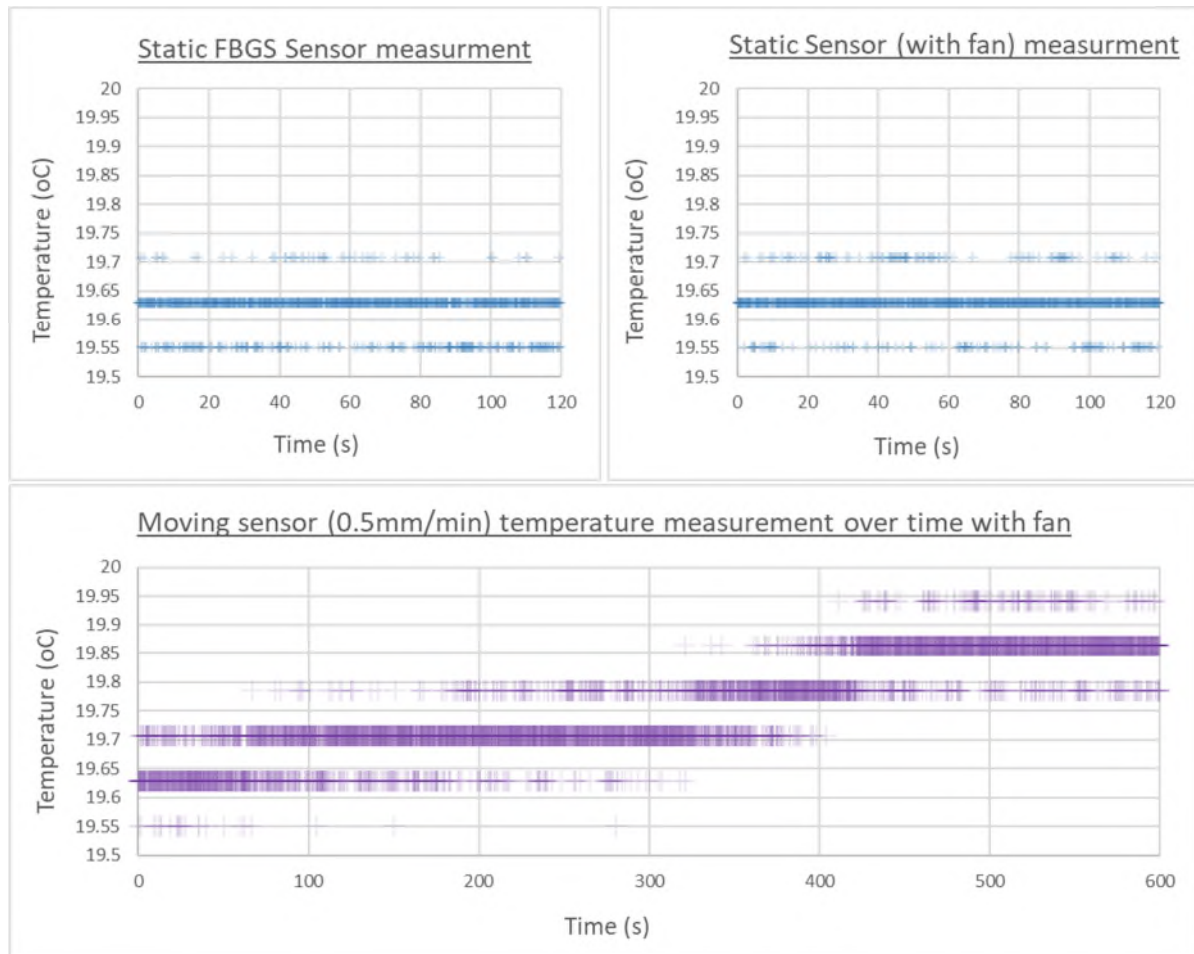


Figure 19 contrasts FBGS temperature measurements across three different conditions, where no gas flow was passed through the torch. Figure 19a (top left) shows the temperature measurement of a non moving sensor across 2 minutes. Figure 19b (top right) displays the temperature measurement of a non moving sensor across 2 minutes with the extractor fan on. Figure 19c (bottom) presents the temperature measurement of a moving sensor across 10 minutes, moving at 0.5mm/min. (Note this was conducted over a five times longer period of time than the previous measurements in a and b, so the 0.2°C increase is likely caused by a shift in atmospheric temperature rather than the strain caused by the sensor movement)

The sensor was moved at a speed of 0.5mm/min, with the extractor fan on, to check the effects of movement on the sensor results. This was compared against the static fibre measurement both with and without the fan. The results show that

just the movement of the sensor alone should not affect the temperature reading by the FBGS due to strain or other physical effects.

The effect of moving the sensor through a flowing gas at 5Lmin^{-1} was also explored. The same set program used for further plasma experiments was used to pass room temperature ($19.5 \pm 1^\circ\text{C}$) argon gas over the sensor.

The sensor showed to be affected slightly by the physical effect of gas flow and read 3°C higher, than without gas flow. The results indicate that this may contribute to the plasma temperature profiles showing a higher gradient of temperature increase, across the jet profile, than what actually occurs.

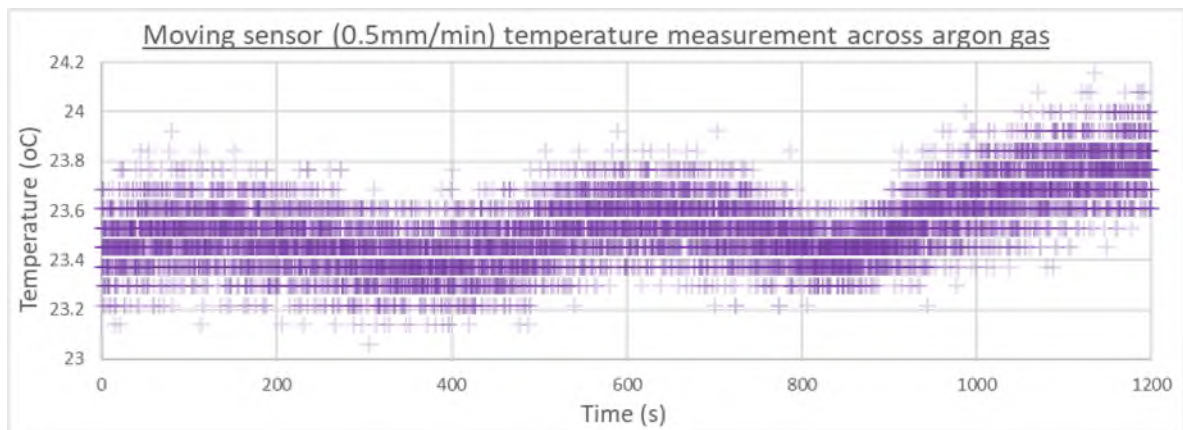


Figure 20 The temperature measurement of a moving sensor across 20 minutes, moving at 0.5mm/min across a flowing of argon gas at 5Lmin^{-1} . Sensor was moved across the Y axis from one side to the other, before returning to the centre of the gas flow before moving to one side of the X axis and back.

4.3 Sensor Response Times

4.3.1 Thermocouple Response Times.

Response times of thermocouples were explored by exposing the thermocouples to the plasma torch at various distances and measuring the time it took for the thermocouple to heat to the plasma temperature. The atmospheric temperature was measured for 8 seconds before plasma exposure.

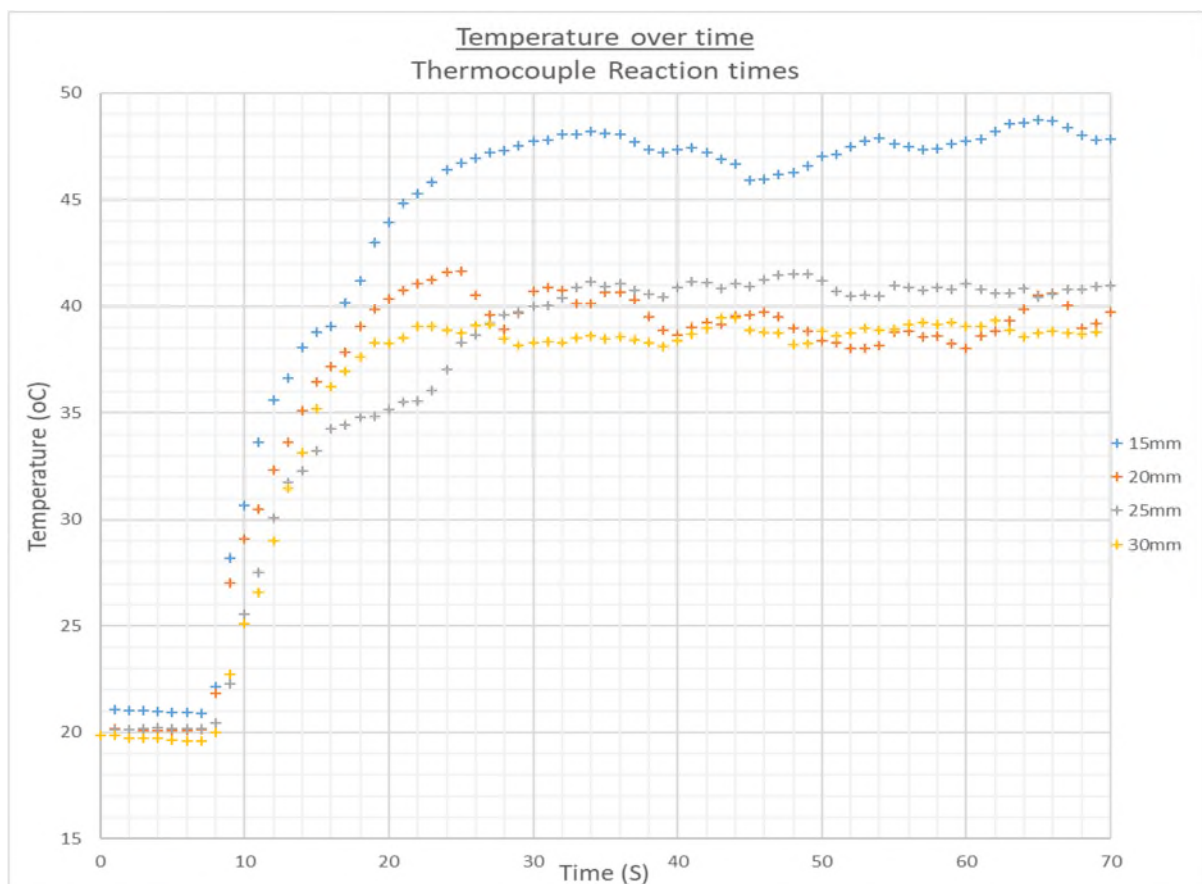


Figure 21 displays the reaction times of thermocouples exposed to plasma at various distances away from the jet nozzle. Atmospheric temperatures were recorded for 8 seconds before plasma exposure. Atmospheric temperature was kept at 20°C +/- 1°C

The results show the thermocouples taking between 10 to 24 seconds to reach thermal equilibrium with the plasma, increasing between 21-28°C

The temperature at various distances from the plasma nozzle was measured between 0 to 20mm away at increments of 0.5mm. The heating times from the decrease in distance was measured of 30 seconds.

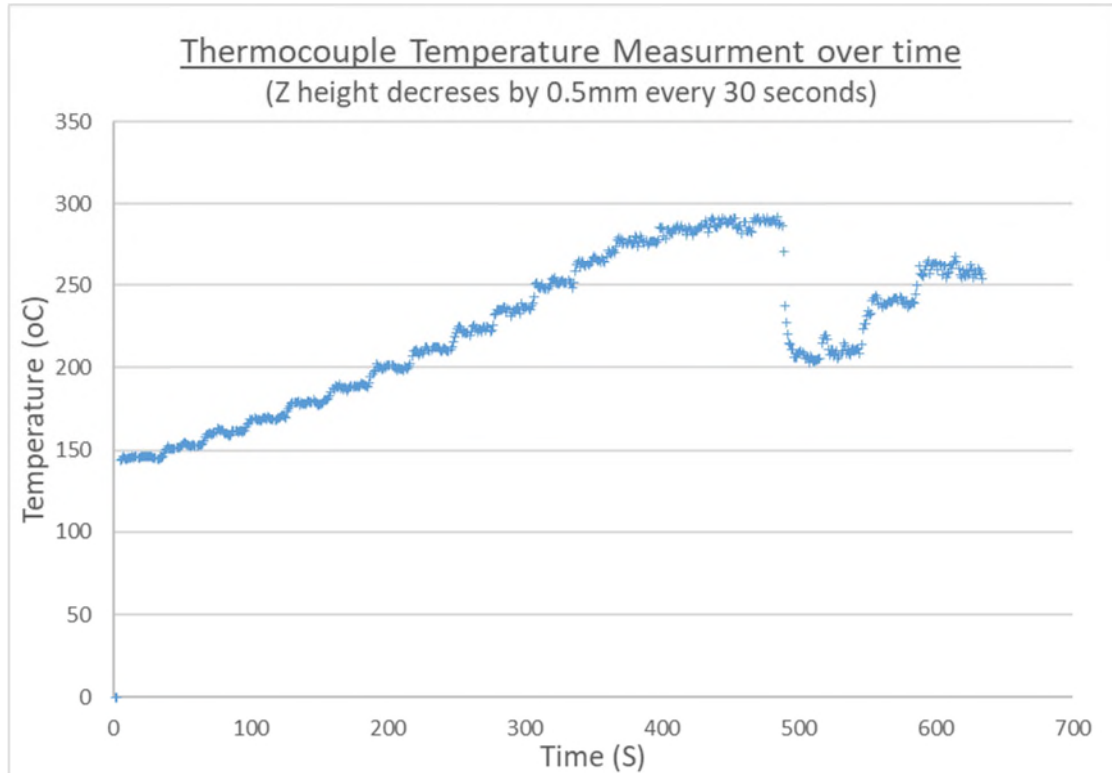


Figure 22 displays the response times of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin-1 and power was 15W. Every 30 seconds the z height was decreased by 0.5 mm. This continued until z=0 after 630 seconds.

3 seconds was taken to decrease the distance after each 30 second cycle. The response times were measured at each distance. Response times between 10mm and 5mm were between 4 to 6 seconds. Temperature difference was also roughly 10°C between each distance. Between 4mm to 3mm temperature increase was considerably small

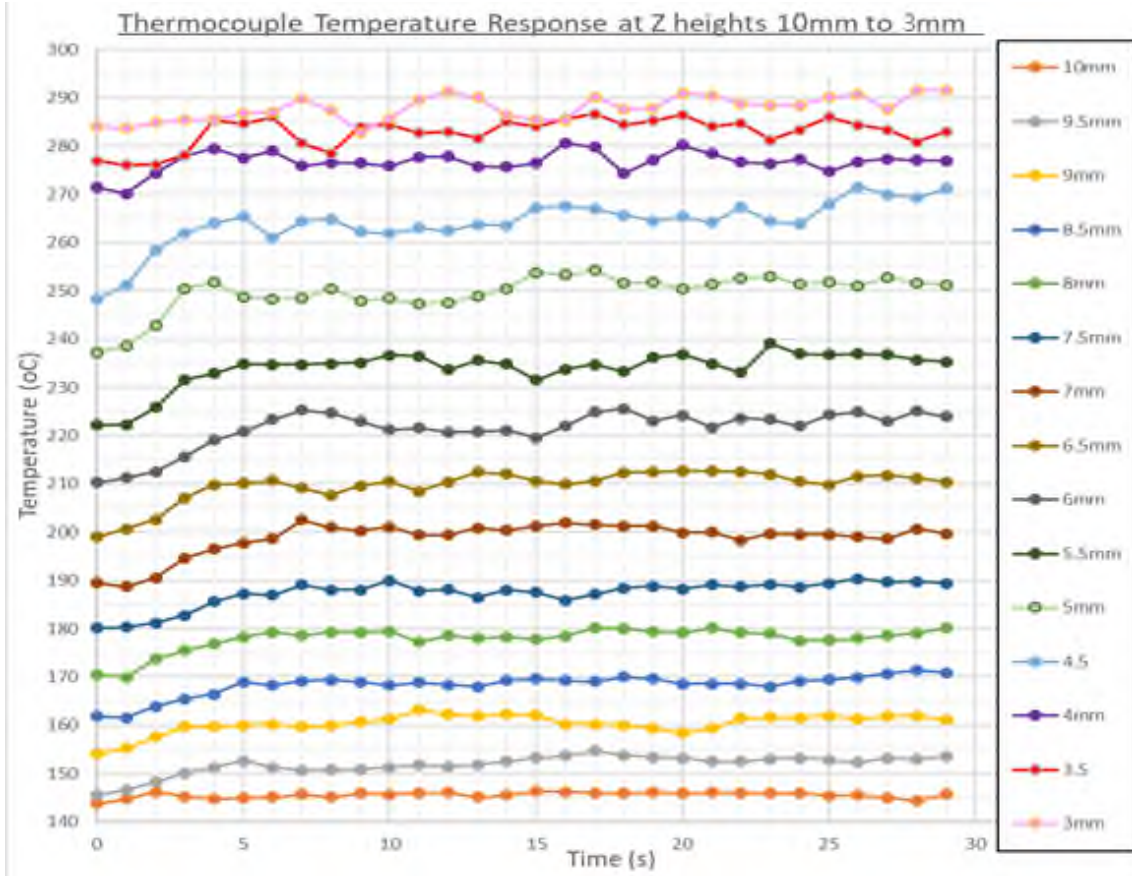


Figure 23 displays the temperature over time of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin-1 and power was 15W. The graph displays response times for Z heights between 10mm to 3mm.(Figure 24 displays the response times at z heights between 0mm to 3mm.) The results show an average thermocouple response time of 5 seconds. They also show that the plasma temperature increases as the z height decreases.

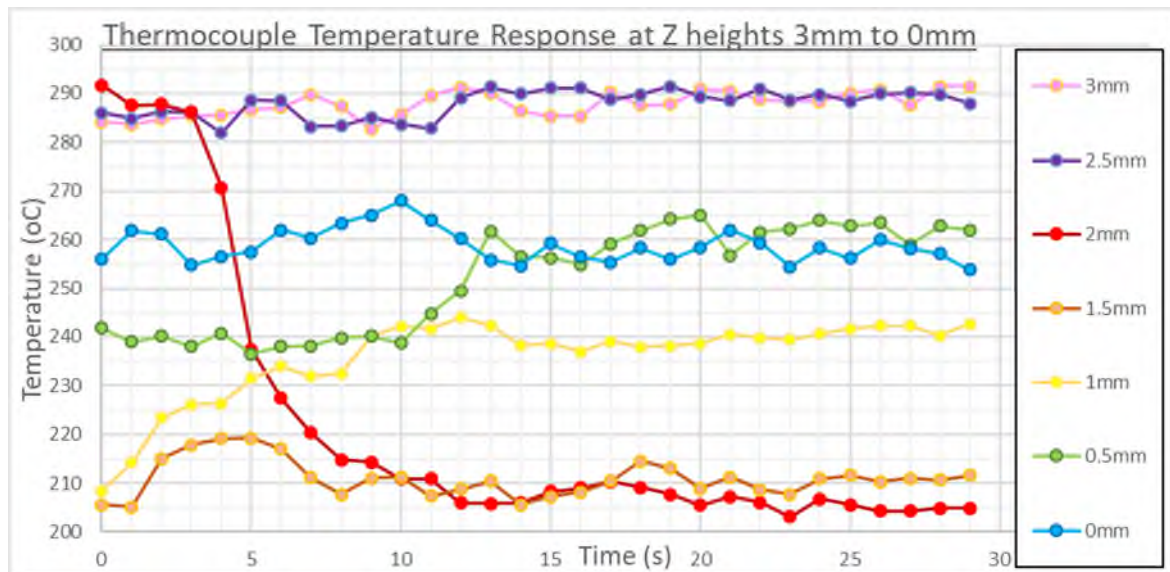


Figure 24 displays the temperature over time of various z height thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 2LMin-1 and power was 15W. Z heights range from 3mm to 0mm. The results show an average thermocouple response time of 10 seconds. Unlike at higher z heights, the temperature reading does not continue to increase as z height decreases. They show that the plasma temperature increases as the z height decreases from 2mm to 0mm, however this is still a lower reading than at higher z heights. When the Z height decreases from 2.5mm to 2mm the temperature measurment quickly drops to over 90°C less.

After holding the temperature a z height of 0 for 60 seconds, the z height of the thermocouples was reduced by 1mm for 60 seconds. Approximately 5 seconds was taken to increase the distances.

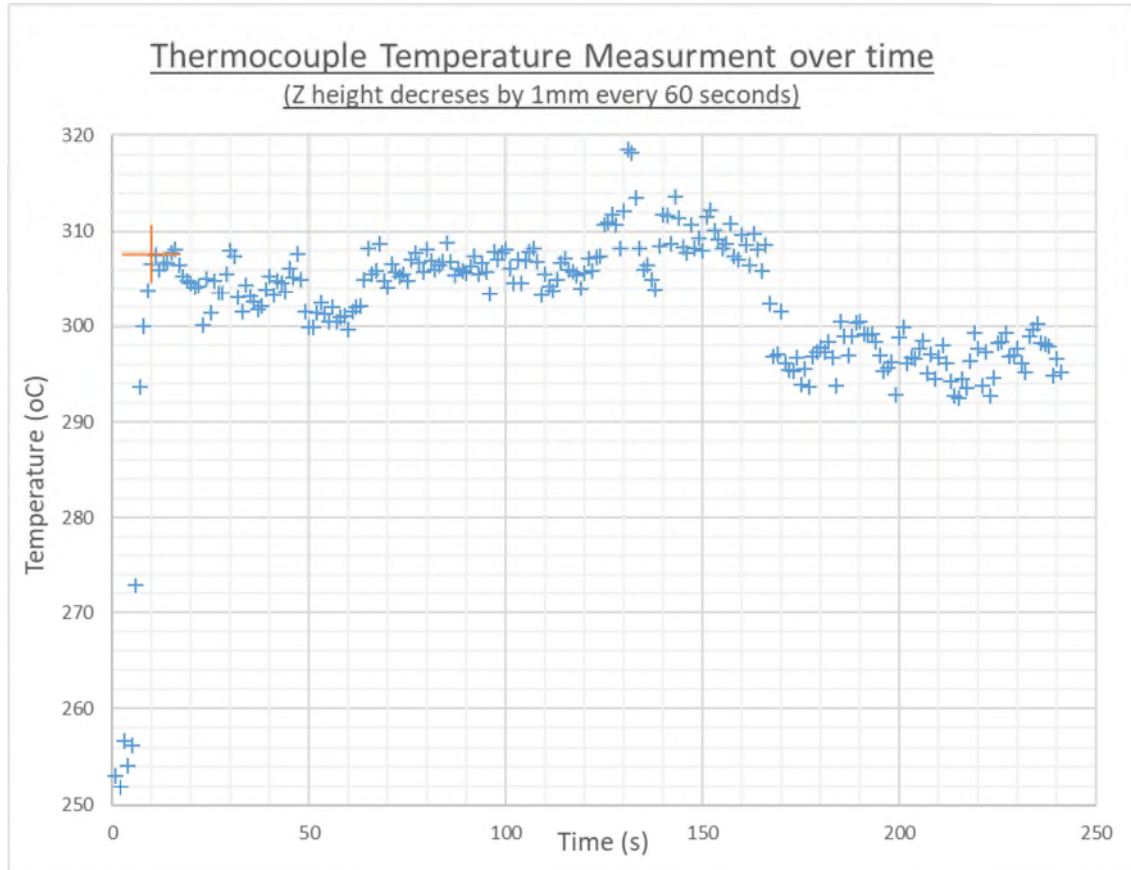


Figure 25 displays the response times of various thermocouples to an exposure by an argon plasma jet at its centre point. Flow rate was 2LMin⁻¹ and power was 15W.

The temperature seemed to increase as the distance was increased until the distance reached 4mm where the temperature seemed to decrease thereafter. This could indicate that between 0 to 2mm z height there is an electromagnetic field of the plasma which could be affecting the reading of the thermocouple.

The experiment was repeated at 5Lmin⁻¹ between 1mm to 4mm z height. Just as the previous experiment, the temperature appeared to decrease at the 2mm and 1mm z heights.

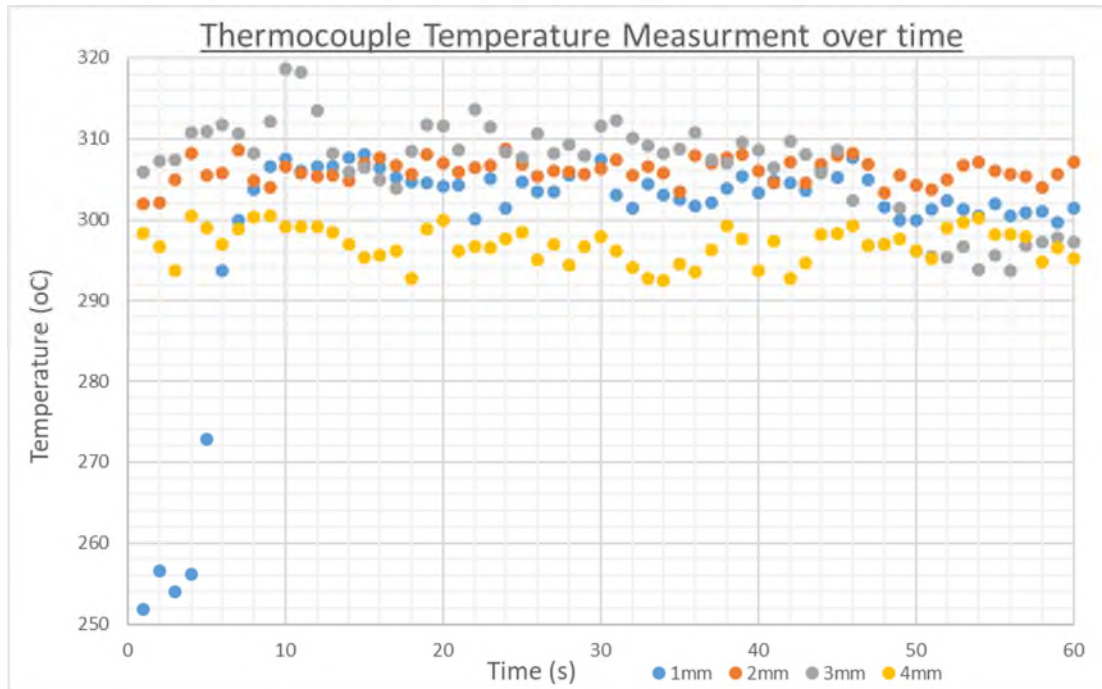


Figure 26 displays the response times of various thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 5LMin⁻¹ and power was 15W. Z heights

4.3.2 Fibre Bragg Grating temperature measurement response times

Response times of the FBGS was explored by exposing the grating to the plasma torch at 2mm (see Figure 27) and 3.5mm (Table 9) measuring the time it took for the thermocouple to heat to the plasma temperature. The results show a response time of 0.5seconds.

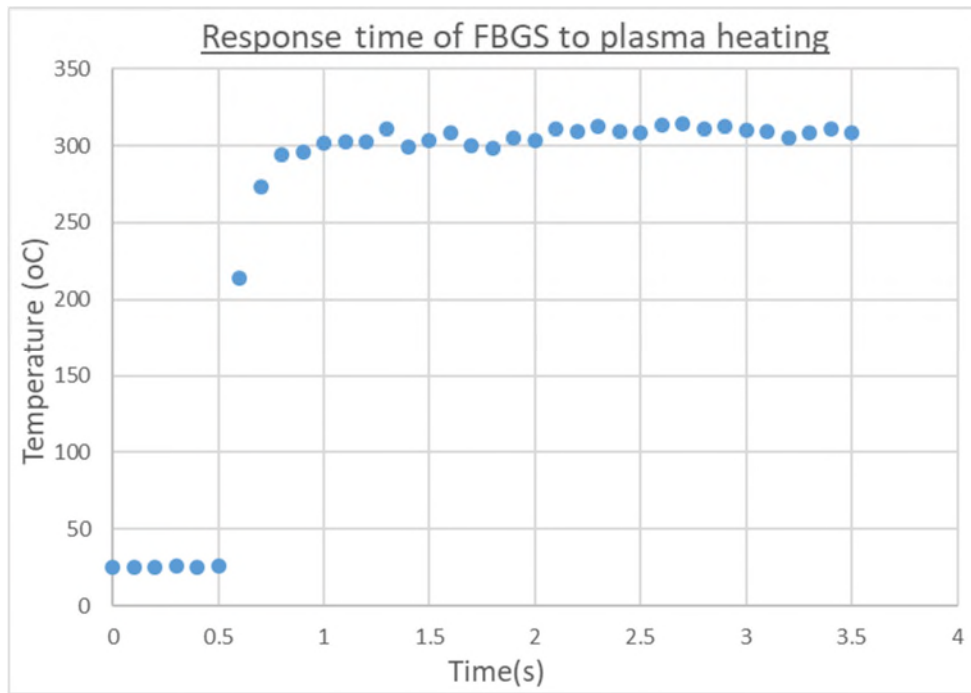


Figure 27 displaying the response times of a FBGS to exposure by an argon plasma jet at it's center point. Flow rate was 5LMin⁻¹ and power was 15W. Z height was 2mm.

4.4 Surface structure visualisation

Fibres were imaged under a Leica light Microscope and a Talysurf coherence scanning interferometer (see Appendix B) to observe the effect of the plasma jet on the surface structure of the fibre Bragg grating.

Images were taken under the light microscope at 5X, 10X, 20X and 40X magnifications. Pre-process imaging showed surface imperfections across the fibre at the sensor region. (See Figure 28 and appendix A.2)

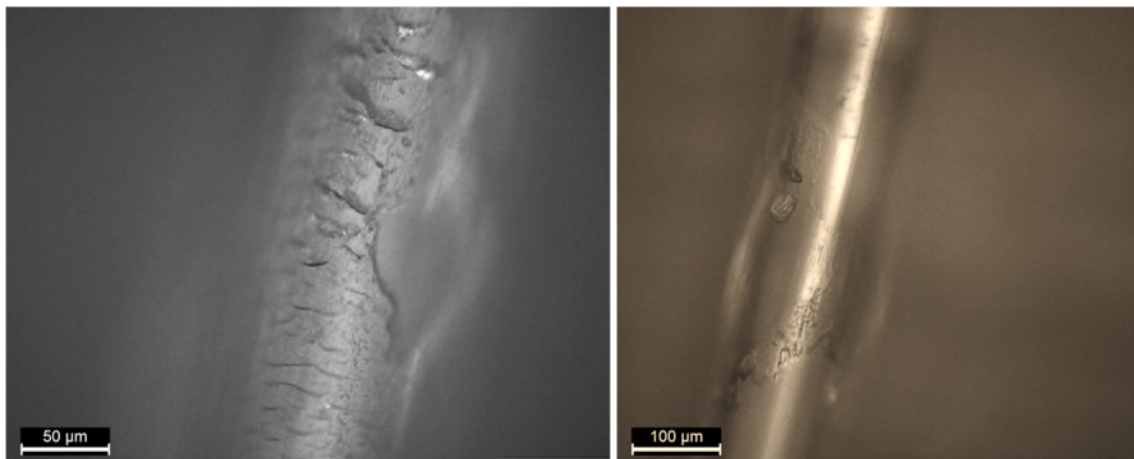


Figure 28 Light microscopy images of the surrounding core of the grating region of a FBGS. Images were taken before plasma processing

Post processing images showed some minor image modifications which could possibly be due to thermal/etching/deposition effects of the plasma. Despite this, the effects on the 125µm cladding was ineffective on the 8µm fibre core, through which the light travels. See Figure 28 and appendix A.2

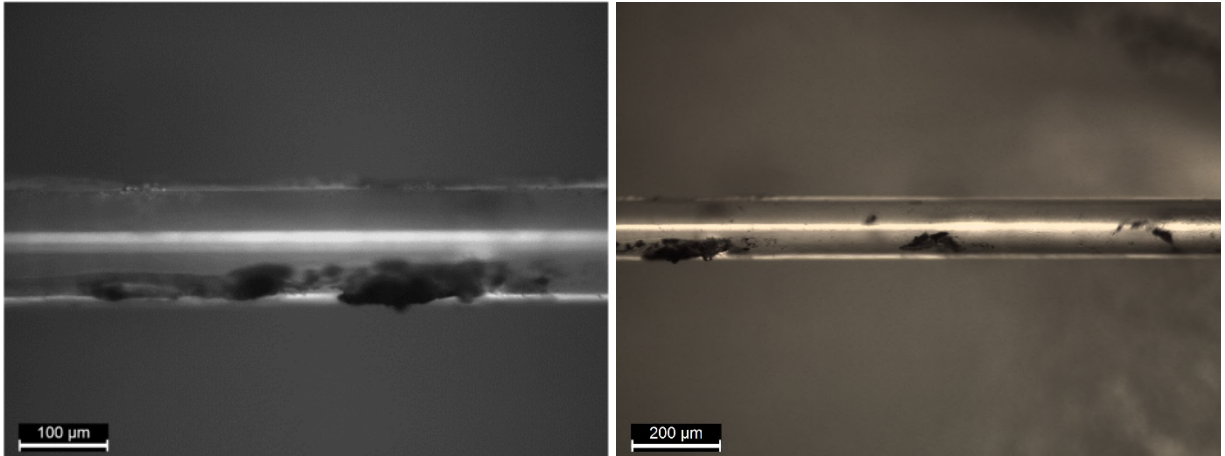


Figure 29 Light microscopy images of the surrounding core of the grating region of a FBGS. Images were taken after plasma processing

4.5 Static Temperature Measurements

Fibre Bragg Grating sensors and thermocouples were used to measure the temperature variation over time in cold argon microwave plasma. Sensors were used to measure the temperatures at two different forward powers; 10w and 15w, as well as two stable flow rates; 1Lmin-1 and 5Lmin-1. These values were taken as they are the relative parameters maximum and minimum values, at where a stable plasma flow may occur.

Lower values were not possible without the risk of extinguishing the plasma. Higher values were not possible due to limitations of the Plasma Tact system.

Efforts to reduced reflective power as much as possible were taken throughout the experiments.

4.5.1 Temperature Measurements over time

The Thermocouple tip and FBGS were placed in the centre of the plasma jet and allowed 30 seconds to reach thermal equilibrium before temperature measurement was taken. Temperature measurements were taken over 60 seconds and 2 repeats taken. Data below shows a 1 minute sample from each parameter combination.

Table 8 displays the parameters used in terms of flow rate and power for each experiment. Although the power input into the system was easily controlled, the power reflected was harder to control, resulting in varied overall powers. The highest possible efficiency with a stable overall power was chosen in each case.

Experiment	Flow Rate (LMin-1)	Forward Power (W)	Overall Power (W)	Efficiency (%)
1	5	15	14.25	95
2	5	11.25	10.41	92.5
3	1	15	13.88*	92.5*
4	1	11.25	10.69	95

*The overall power of the system was not stable with the reflective power spiking up to 50% reflective power and back down 7.5% over the span of less than a second, across the temperature measurement period. The reflected power was raised to 10% (reducing the overall power to 13.5W) in an effort to increase the jet stability although it did not prove helpful.

4.5.1.1 Overall Results

The results of the thermocouples and fibre Bragg gratings vary considerably, with thermocouples reading much lower than that of fibre Bragg gratings. Thermocouples indicated that power increases contribute the most to an increase in temperature, while FBGS indicate that a decrease in flow rate will result in the most considerable temperature increase. Although both temperature sensors indicated that higher powers increase temperature, Thermocouple data indicated that a rise in flow rate indicated a rise in temperature, while this was the opposite case for FBGS. The experiment for both sensors was repeated and returned similar results. One possible reason for the apparent increase in temperature, with increase in flow rate, as shown by the thermocouple is that electron densities increase at higher flow rates. This could have resulted in more electrical interference at the thermocouple's reading (Mariotti et al., 2007) (Hashim, Aadim and Rustom 2017) (Humud, Abbas and Rauuf 2015).

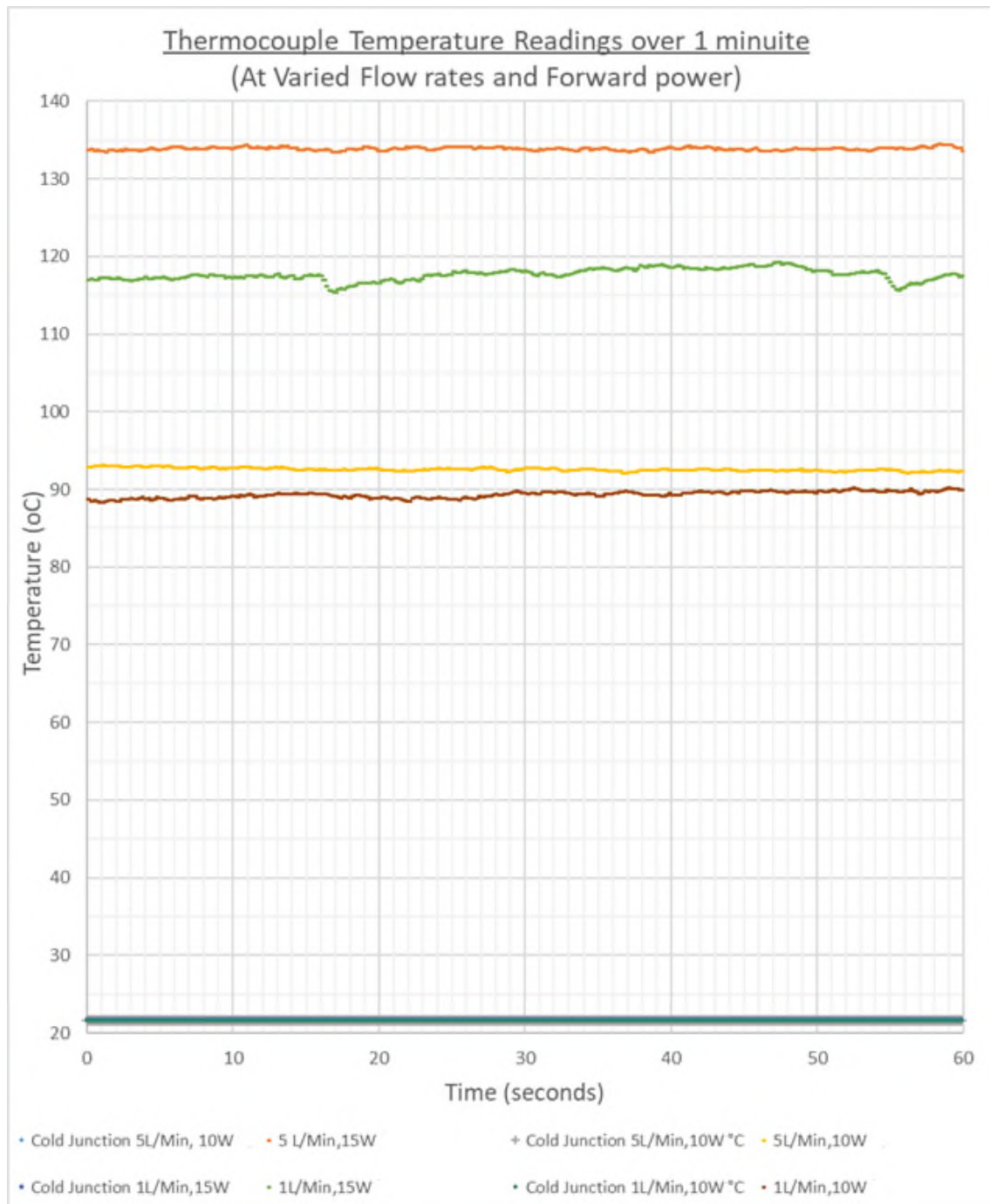


Figure 30 Temperature measurements of a static thermocouple over 1 minute. Results show lower flow rates produced lower temperature readings.



Figure 31 Reflected wavelength measurements of a static FBGS over 1 minute. Results show lower flow rates produced higher temperature readings.

Nozzle to sensor distance	Average Temperature (°C)			
	5L/min 15W	5L/min 11.25W	1L/min 15W	1L/min 11.25W
2mm	290	170	710	470
3.5mm	245	155	662	429

Table 9 displays a comparison of the temperature recorded from a FBGS, of two various Z heights, in measuring the effect of flow rate and power, in argon plasma jet temperatures.

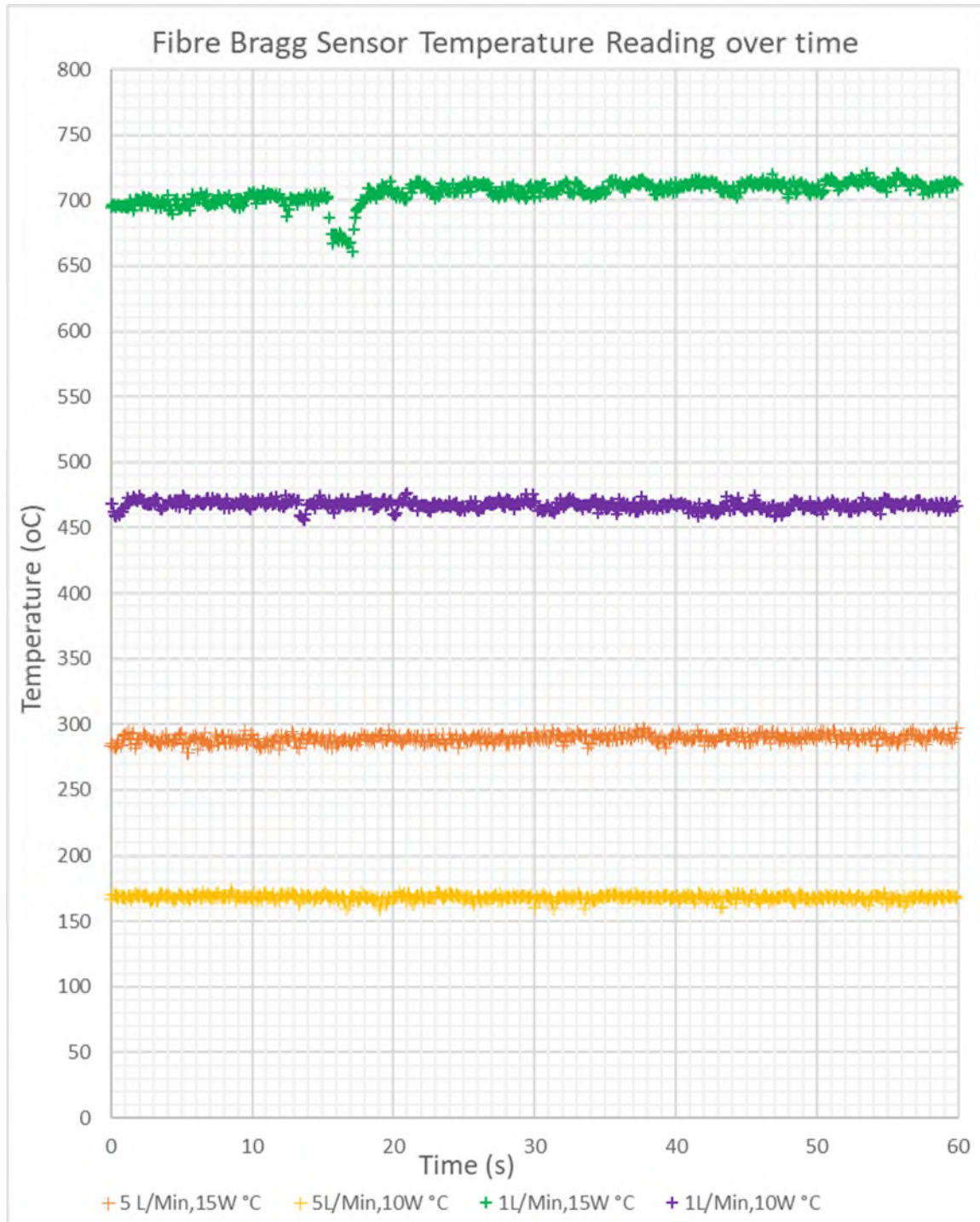


Figure 32 Temperature measurements of a static thermocouple exposed to a plasma jet over 1 minute, at varied flow rates and power. Results show lower flow rates produced higher temperature readings.

4.6 Z height Experiments

The effect of Z heights (the distance between the nozzle and the temperature sensor) in temperature sensing was explored initially in thermocouples, and then eventually in the FBGS.

4.6.1 Thermocouples

Z height was particularly explored in thermocouples, as literature suggests that (Van Gessel, 2012) thermocouples are less effective, the closer they are to the centre of the plasma jet. Often thermocouples are used as methods to measure the air temperature around a plasma (source), or used within the generator (source), rather than within the plasma itself.

Section 4.3.1 fully explores the effect of Z heights on the thermocouple's reading ability. In Figure 24 displays the temperature over time of various z height thermocouples to an exposure by an argon plasma jet at it's center point. Flow rate was 2LMin-1 and power was 15W. Figure 24 a sudden drop in temperature is observed at 2mm Z height, with the temperature then gradually building up again as the thermocouple gets closer. This indicates that the plasma could cause the thermocouples to provide incorrect readings

4.6.2 Fibre Bragg Gratings

The effect of changing Z heights was also observed. The FBGS was tested at z heights from 0 to 110mm to ensure there were no unusual results which mimicked that of the thermocouple.

Table 9 in section 4.5.1 shows the average temperatures of the FBGS measurement at 0.2mm and 3.5mm. As expected the temperature decreases as Z height increases.

Figure 33 displays the contrast between temperature measurements at 100 and 101mm from the sensor nozzle, with a jet using 15W forward power and 1Lmin^{-1} flow rate. Overlap in temperature reading occurs, with temperature ranges being very high. Ranges of up to 70°C can be observed during these temperature measurements, which is likely a cause of strain induced from the flow rate. Figure 34 display the average temperature at Z heights from 100 to 110mm. A near linear decrease in temperature is observed as z height is increased.

Results show a high temperature range which could be due strain on the centre, or the need for nonlinear calibration at high temperatures.

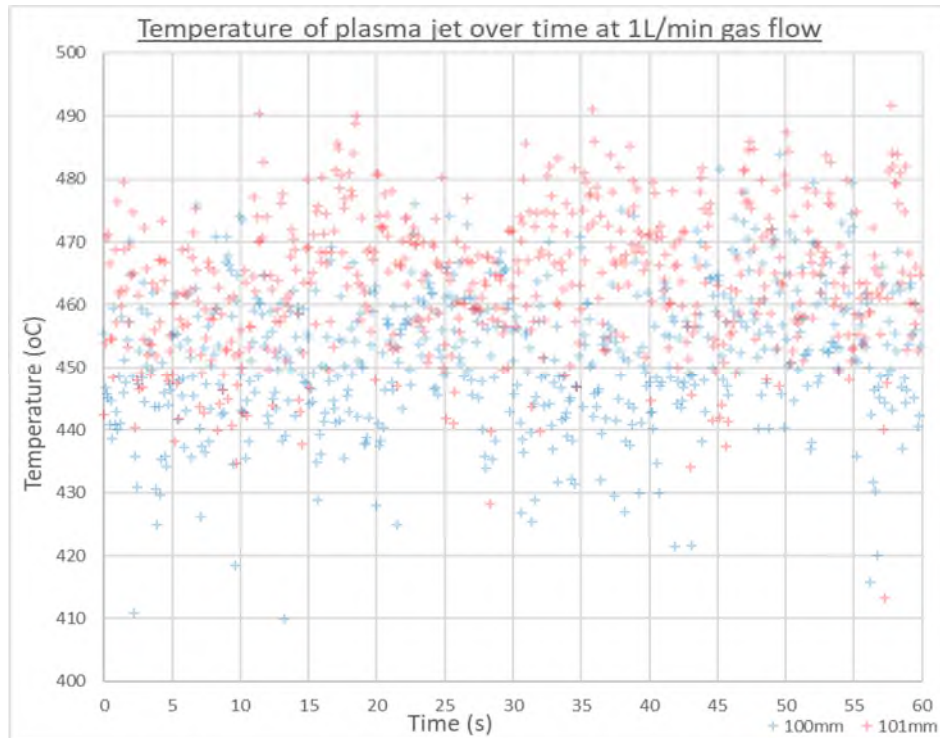


Figure 33 displays temperature readings at 100mm and 101mm z height using a FBGS at the center of a MW argon plasma at 1L/min.

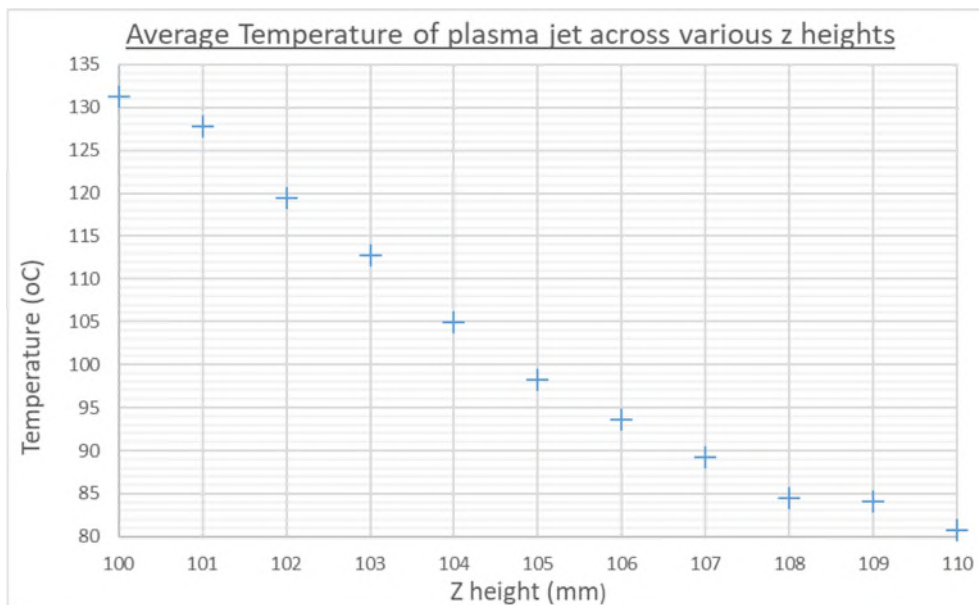


Figure 34 displays average temperature readings at varying z heights from 100mm to 110mm z height using a FBGS at the center of a MW argon plasma at 1L/min.

4.7 Spatial Profiles of the plasma temperature (Microwave cold plasma)

Several temperature profiles were produced by passing the sensor through the jet in the x and y directions, recording the temperature with fibre Bragg gratings and thermocouples

As found in 4.5, the temperature profiles also indicate that FBGSs are reading temperature measurements much higher than that of thermocouples.

In both cases, a z height of 2mm was used with a flow rate of 5Lmin⁻¹ and a power of 15w. Primarily, for temperature profile measurements made in Y, the measurements were taken at the centre of the jet, or 'X = 0'. The reverse can be considered for temperature profiles in the X direction.

Both temperature measurement devices showed similar temperature distributions. It may appear in both cases that temperature is normally distributed across the profile of the plasma jet, however there appears to be a skew in the distribution. This is likely the cause of the plasma jet being affected by the running extractor fan near by the jet, causing the shape of the jet to skew slightly.

4.7.1 Thermocouples

Thermocouple Profile was taken by passing the thermocouple through the jet at 1mm/min to reduce the effects of the thermocouple reaction times. TC was mounted on PTFE to rule out effects from substrates. Thermocouple was able to show the general distribution of the jets temperature although electromagnetic interference can be observed in the rapid temperature spikes across the measurement. The results also show the plasma heating the ambient air temperature considerably around a 2mm radius around the plasma diameter.

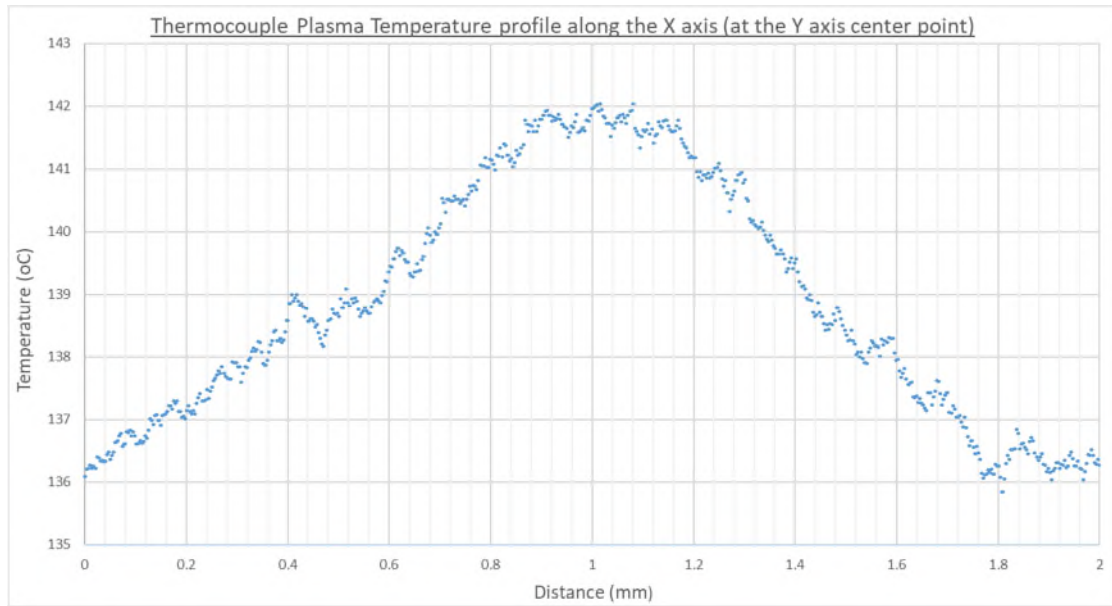


Figure 35 displays the X axis temperature profile of a 5L/min, 15W microwave plasma jet, across its 2mm diameter, as measured by a thermocouple.

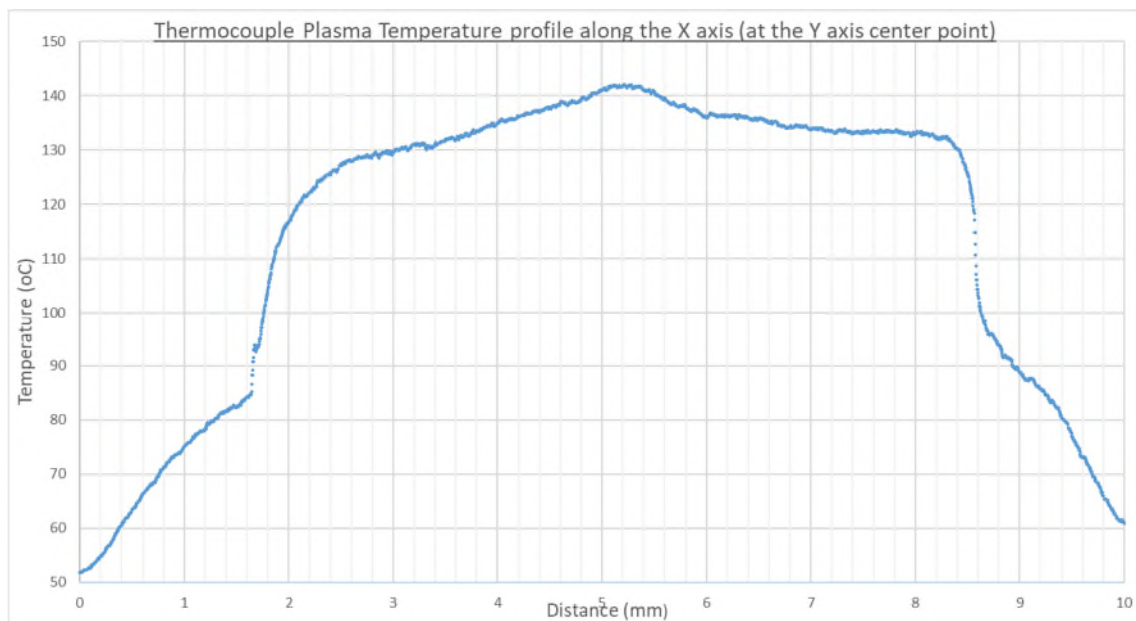


Figure 36 displays the X axis temperature profile of a 5L/min, 15W microwave plasma jet, as well as the surrounding air temperature across 10mm , as measured by a thermocouple.

4.7.2 Fibre Bragg Grating

Temperature profiles were conducted initially to measure the temperature profiles across the plasma only, and then repeated to measure the temperature across the jet and the surrounding air, which is likely to undergo heating as a result of the plasma.

4.7.2.1 Trial Experiment

The first experiment conducted showed promising results, however there was a lot of interference from the strain upon the sensor, causing the reflected wavelength to spike, resulting in wavelengths too high for the interrogator to scan. As a result the data, as shown in Figure 37 appears missing at certain distances.

The results of this experiment indicate that there was improper structural support for the fibre Bragg grating. As a result, a PTFE and MACOR substrates were designed with 0.3mm milled groove to accommodate the fibre, with minimum disruption from the sensor to the plasma, while also improving rigidity.

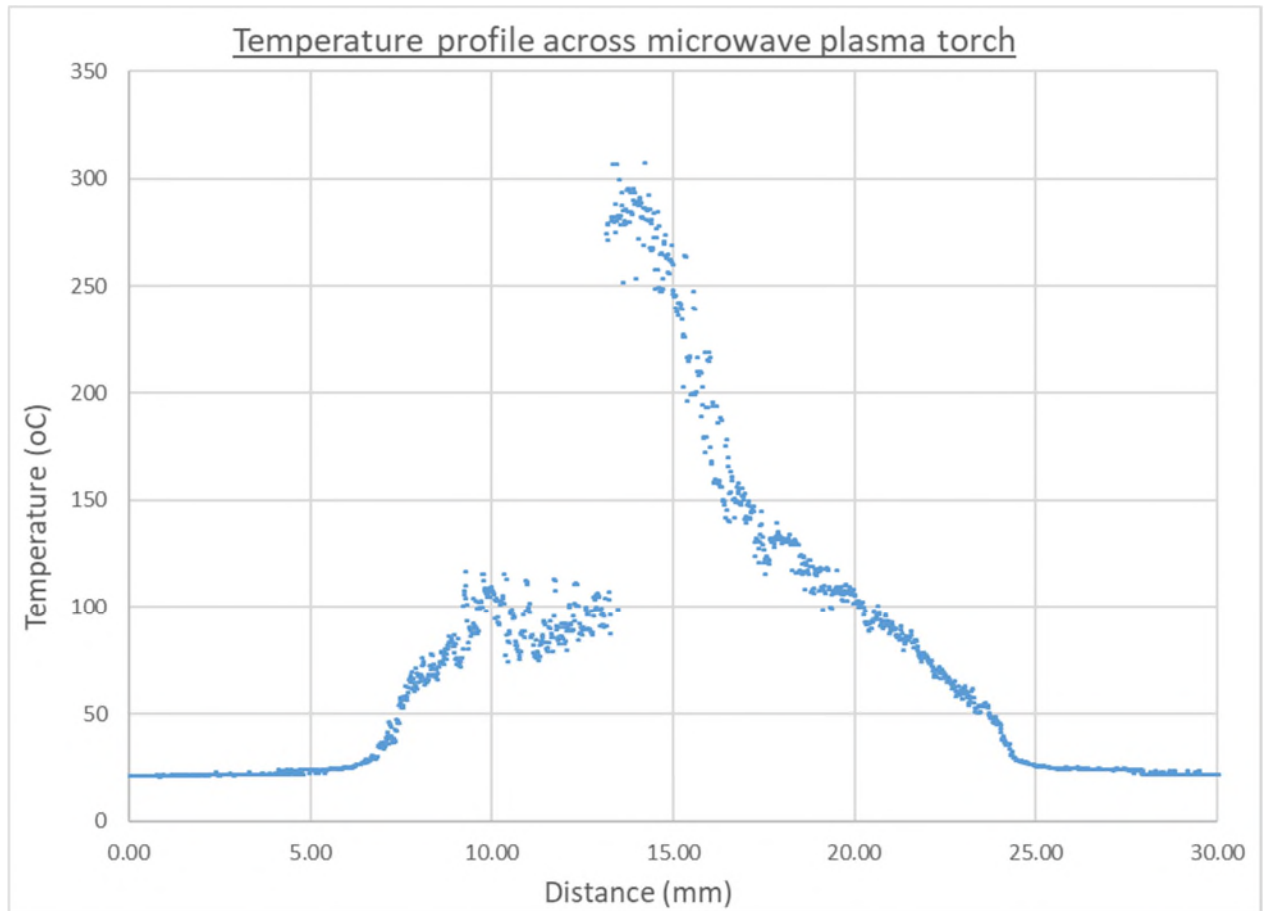


Figure 37 displaying an initial train experiment using a FBGS to measure non thermal microwave plasma, unrestrained. The motion stage moved at 10mm min^{-1} and the flow rate of the plasma was 5Lmin^{-1}

4.7.2.2 Profile Characterisation

The initial temperature profile of Y Figure 38 showed that the temperature gradient from the hottest point of the jet (at 1.2mm), towards the air, was equal on both sides of the jet, despite the apparent skew of the graph. A large temperature measurement range was shown which was similar to the results of Corre et al., (2018) who also found the accuracy of measurement to be 10°C . It is likely that the temperature measurement of any space in the profile of the MW plasma results can be said to be accurate to $\pm 5^{\circ}\text{C}$

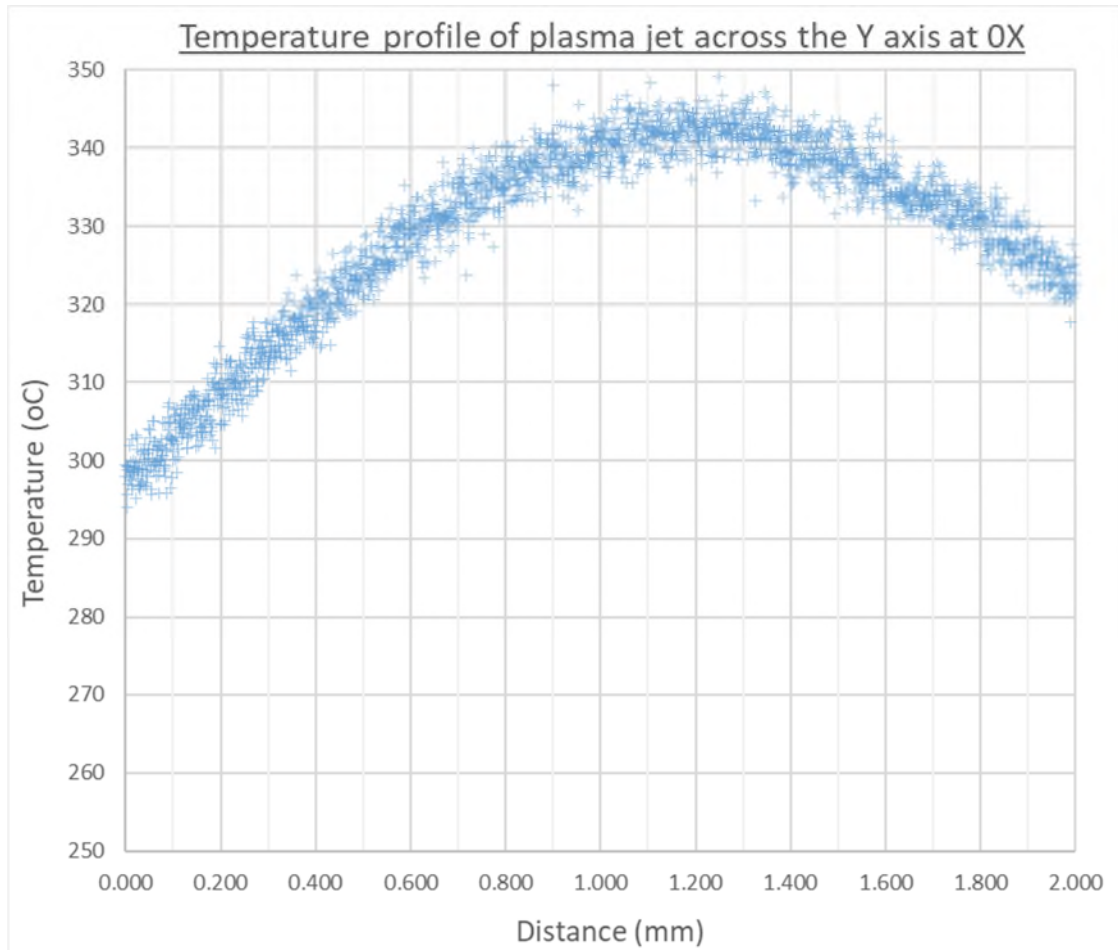


Figure 38 displays the temperature profile of an argon MW plasma jet using a FBGS across the Y axis. Power was set to 15w and flow rate was 5Lmin⁻¹. Results show temperature of the jet ranges from 300 to 350°C.

This skew is further noticeable looking at the 4mm distance measurements where there is a lot steeper gradient towards one side the plasma than the other as seen in Figure 39. This would indicate that the extractor fan is further affecting the results due to its position to the side of the torch, unevenly cooling the air around the torch.

The x axis provides somewhat more intriguing results. Again, here in Figure 40 the slope appears to be near equal on both sides from the highest temperature point, however it appears there is a small temperature spike near the 0 distance point. Looking at the extended profile, Figure 41 the temperature seems to increase in the surrounding area at one side of the jet. This could be due to the shielding of the surrounding air by the jet, preventing cooling from the fan and

hence increasing the temperature, or as a result of a different heat source, although it is not apparently clear what this could be.

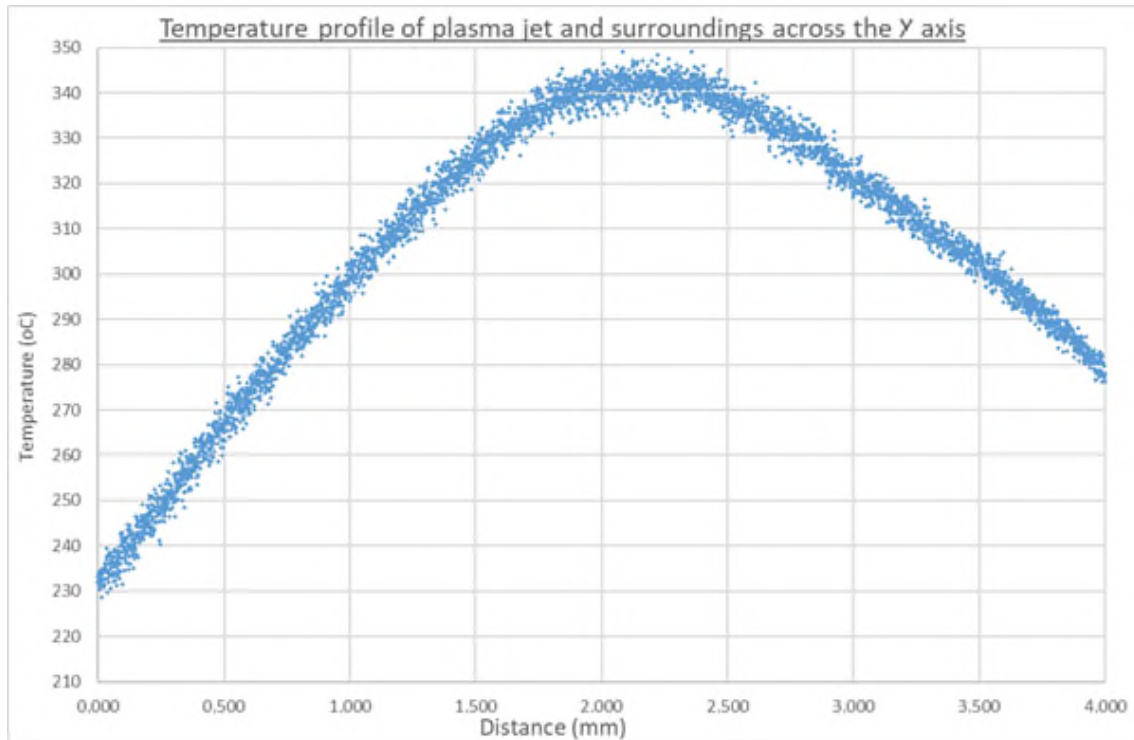


Figure 39 displays the temperature profile of an argon MW plasma jet and surround air using a FBGS across the Y axis over 4mm. Power was set to 15w and flow rate was 5Lmin^{-1} . Results show temperature of the jet ranges from 300 to 350°C , while ambient air temperature ranged from 230 to 320°C .

Figure 39 displays a non-symmetrical curve, this is likely due to the extractor fan in the experiment affecting the shape of the jet.

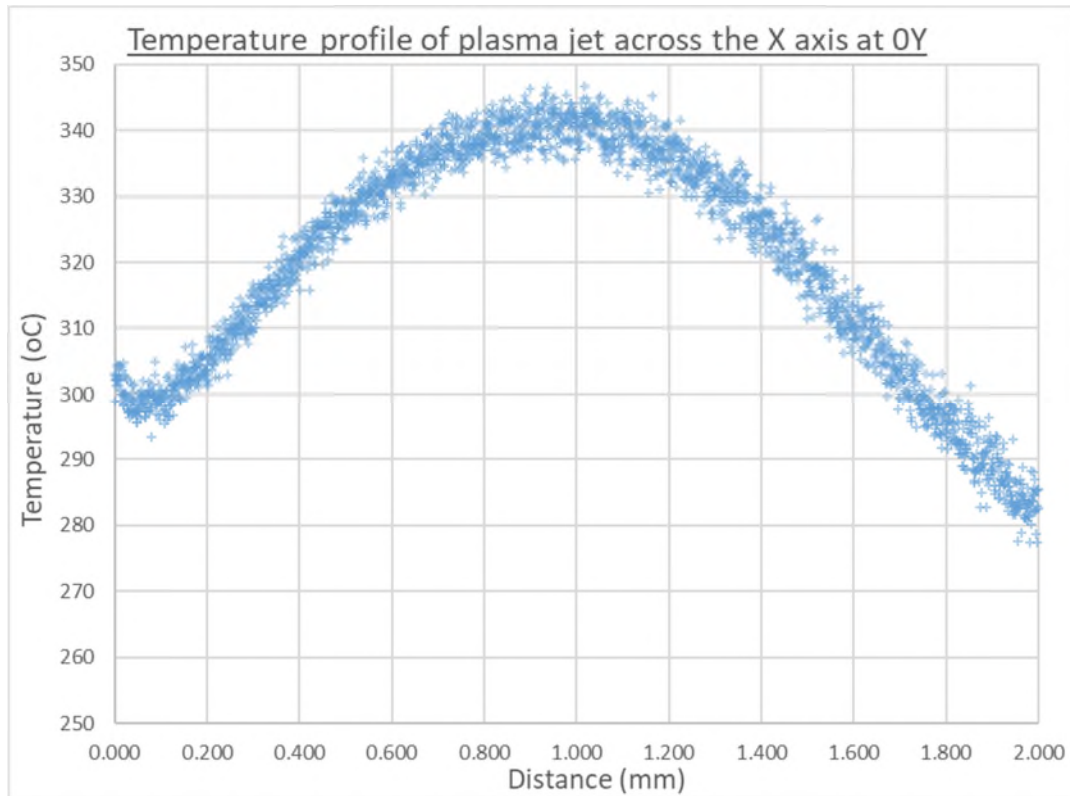


Figure 40 displays the temperature profile of an argon MW plasma jet using a FBGS across the X axis. Power was set to 15w and flow rate was 5Lmin-1. Results show temperature of the jet ranges from 280 to 350°C

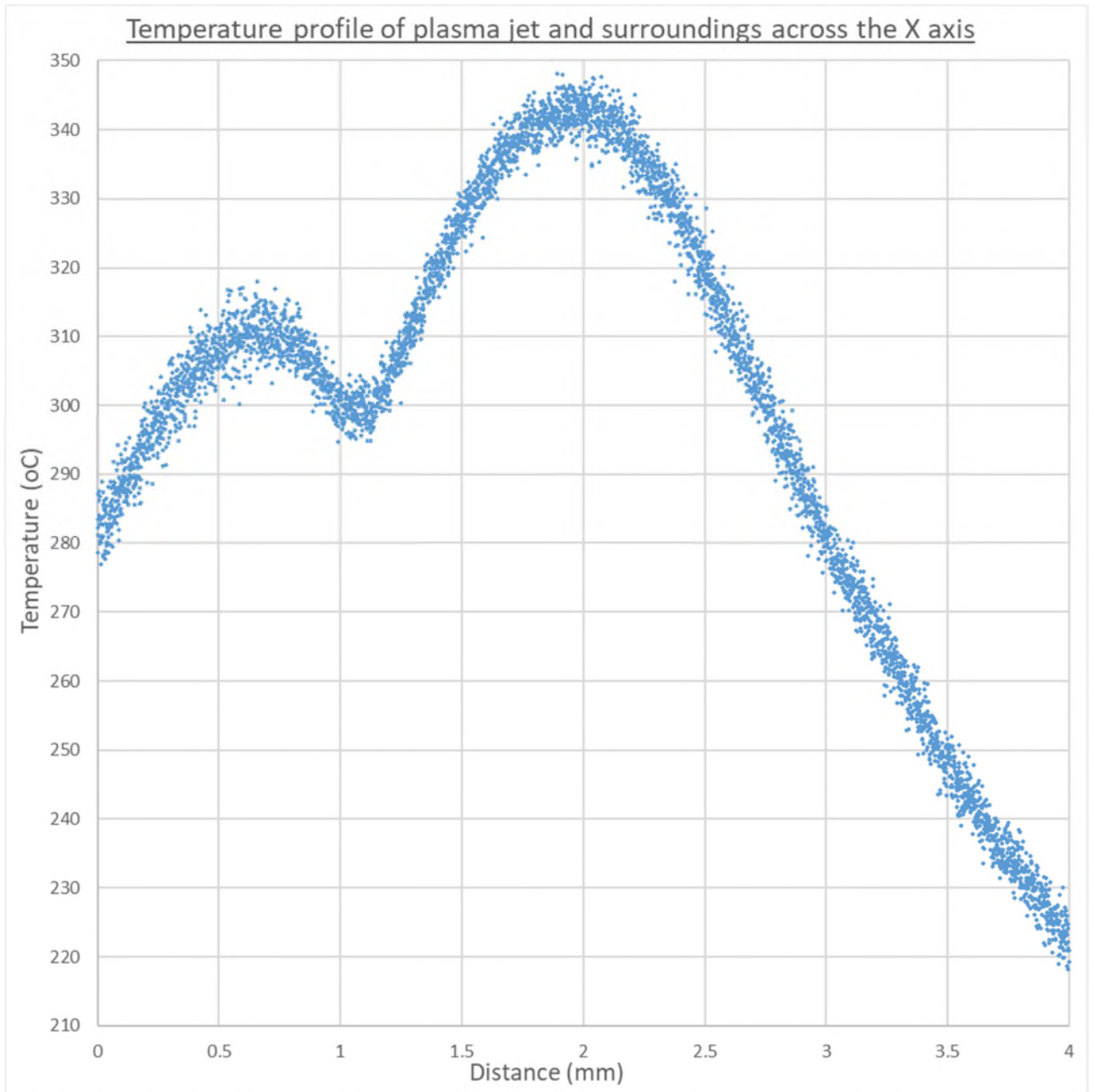


Figure 41 displays the temperature profile of an argon MW plasma jet and surround air using a FBGS across the Y axis over 4mm. Power was set to 15w and flow rate was 5Lmin⁻¹. Results show temperature of the jet ranges from 280 to 350°C, while ambient air temperature ranged from 220 to 300°C

4.7.2.3 Effect of Varying X distance, on temperature profiles in Y direction

The temperature profile of the jet was explored in y, at multiple heights of X, to observe if it would in turn result in profile changes. Figure 42 displays the temperature profile across the jet, and surrounding air, at 4 different x heights, ranging from 0mm to 5mm. Results show similar profiles for each distance, with temperatures reaching similar values as the sensor travels away from the jet into the surrounding air. The difference in temperature between each profile is greatest at the Y axis centre point, and under the jet in general. The data indicates significant temperature gradients from the centre, to the outer regions of the plasma.

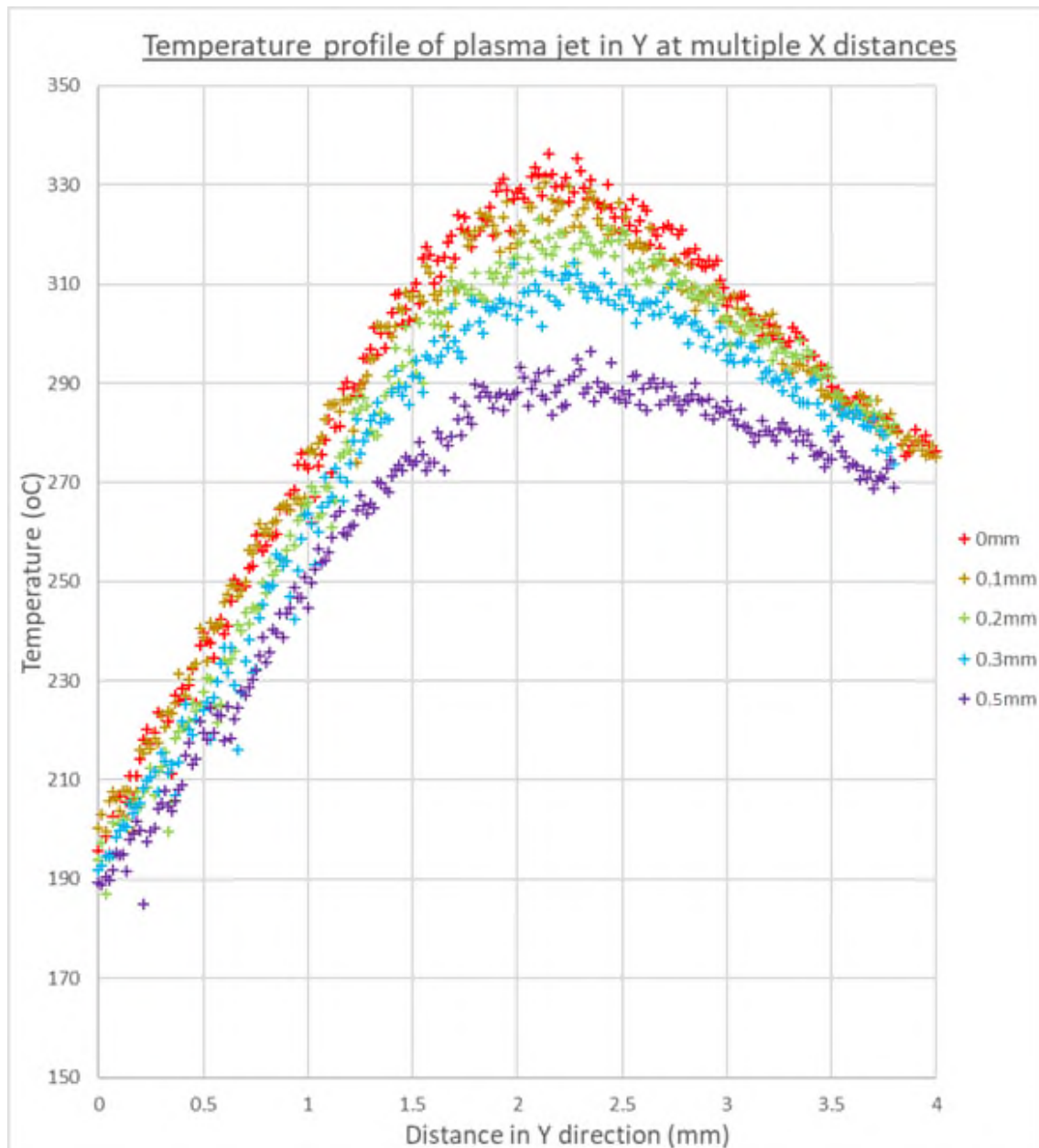


Figure 42 Temperature profiles of the Argon plasma jet across Y. Profiles were taken at the center point ($X=0$) and at 0.1mm, 0.2mm, 0.3mm and 0.5mm from the center point.

4.8 Temperature Profiles (radio wave thermal plasma)

Temperature profiles were also measured across an inductively coupled RF thermal plasma torch. These were measured by the FBGS only due to the high heat and electromagnetic field. As the torch has a diameter of 18mm, the sensor should be able to provide a relatively more accurate profile of the torch temperature profile. Instead of measuring a profile of X and a profile of Y, 22 Y axis profiles were measured from -4mm to 18mm across the X axis, where the centre of the plasma is X=0. The motion stage passed the sensor across the jet at a speed of 10mm/min, until it reached a distance of 100mm where the stage moved +1mm in the X direction. This is shown in Figure 43, Figure 44 and Appendix D.

The RF plasma has a gas flow rate of 15L/min⁻¹ and a forward power of 991w with 10w reflected. The ambient temperature of the chamber was measured to be between 35 to 43°C during measurement, likely due the plasma heating up the surroundings.

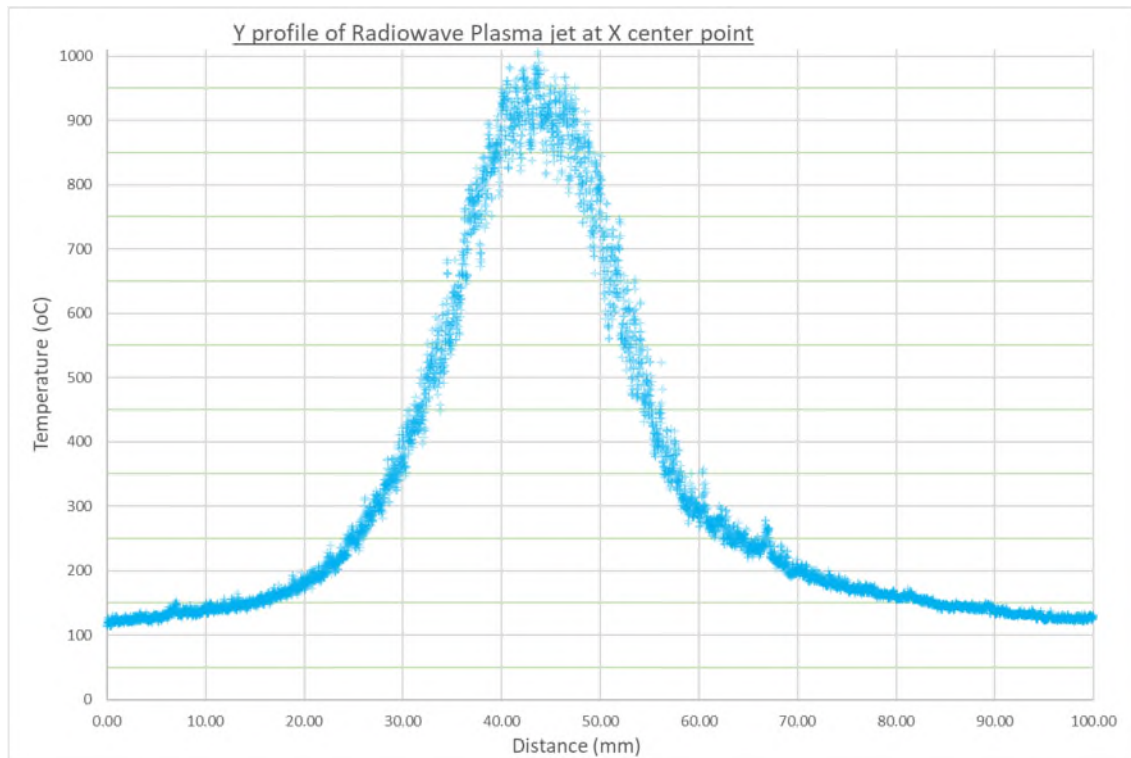


Figure 43 displays the Y axis temperature profile, across 0X axis position.

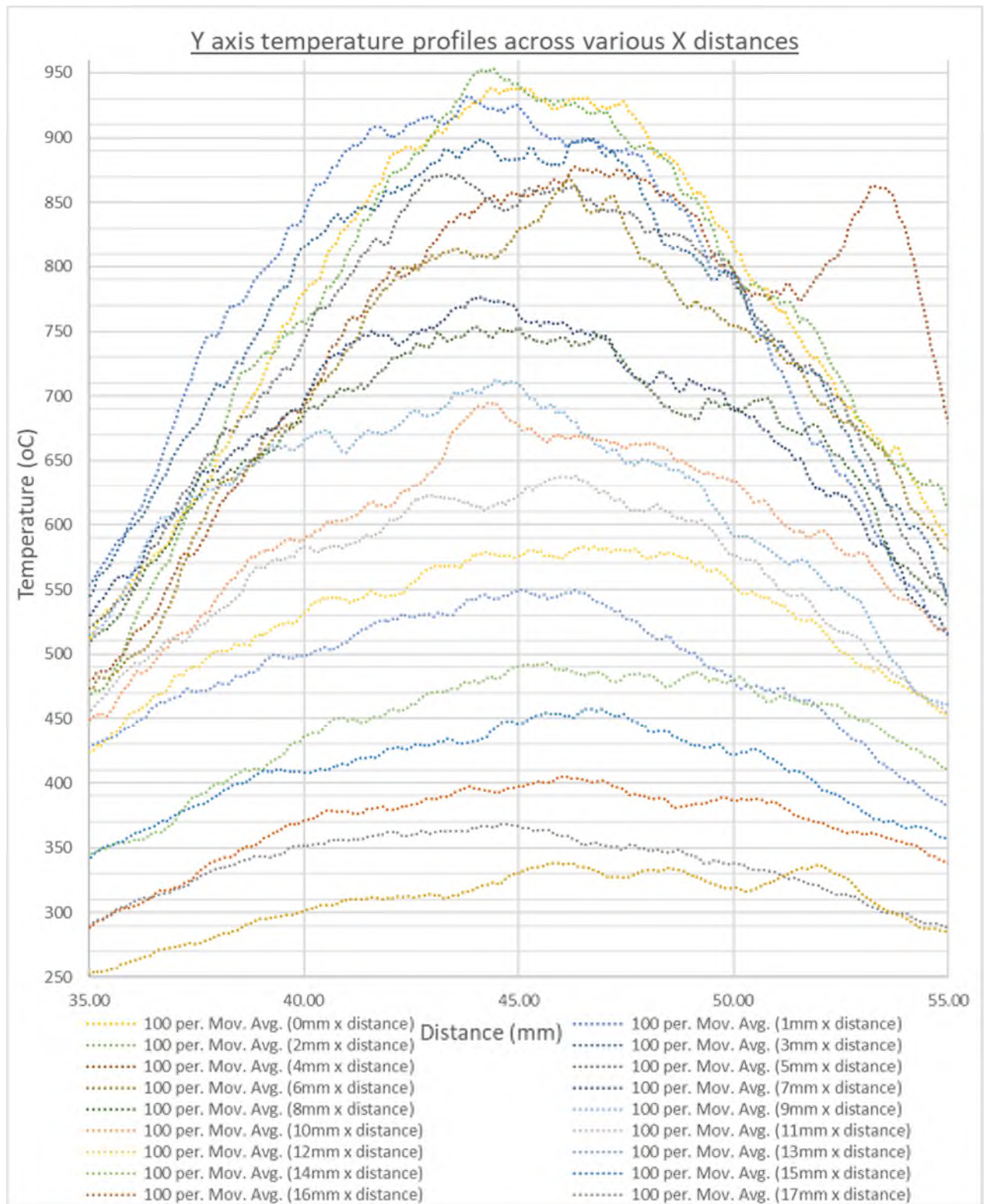


Figure 44 displays the Y axis temperature profiles, across 22 X axis positions ranging from 0mm to +18mm from the centre of the jet. Data shows an average point over 100 results.

5 Discussion

5.1 Non Plasma Temperature measurements

FBGS are used primarily to measure two things; Strain and Temperature (Güemes and Messerve, 2010). Unfortunately this makes it difficult when exposing a FBGS to a new environment, to ensure that a temperature measurement is isolated from effects of strain.

Several sources of strain were considered in the experiments such as effects from the extractor fan, moving table, or most importantly, from the flow of the argon gas. Results showed that increasing flow rate of argon gas may have some small effect on increasing the strain and hence increasing the perceived temperature reading.

It was also shown that the extractor fan's influence has negligible effect to the FBGS temperature reading. The movement of the table is also unlikely to effect the results.

One source of strain and effect on temperature is likely effect of the argon gas flow over the FBGS. Figure 20 shows that the position of the sensor across an argon jet could affect the measurement by 0.2°C. This is a small but noticeable difference in recorded temperature. However this small temperature increase is unlikely to have noticeable effects on the results of this experiment.

Venkatesan et al., (2017) conducted measurements of mass flow rate using FBGSs for cryogenics, with a second sensor added for temperature measurement, parallel to the flow path. Their results showed an increase in Bragg wavelength as the mass flow was increased from 0 to 5 g/s. Helium gas of 5 g/m at 298K produced a wavelength shift of about 120 to 140 pm compared to no gas flow. This could equate to a perceived temperature increase of around 10°C, depending on the FBGS sensitivity.

This experiment mainly focused on flow rates between 1 L/min to 5 L/min, several times higher than those explored in Venkatesan et al., (2017). This could indicate that flow rate should have a stronger effect on temperature readings.

5.2 Response times

Response times can be particularly important in temperature sensing in general, not just for applications in plasma. The experiments here showed that thermocouples (TCs) can take over 10 seconds to measure a 20°C temperature increase. Although the thermocouple can react quickly to smaller increases in temperature, these do not compare to that of a FBGS which we have shown to be able to measure a temperature increase from 25°C to 300°C in less than half a second as shown in Figure 27.

Knoerzer et al., (2012) found that their T-type copper-constantan wire thermocouple took 17 seconds for response time unsheathed, and 20 seconds grounded.

They speculate that the differences between thermocouple response times and that of a fibre optic probe is due to a variation of the thermal masses of the sensing elements of each device. I.e. the thermal mass of the TC tip is likely to be much higher than that of the fibre's borosilicate glass core.

5.3 Surface structure effects

Microscopy did not show any noticeable effects which could be observed from the argon plasma jet onto the FBGS. Although the fibre cladding appeared damaged, this is likely caused by handling rather than effects of the plasma itself. Kocatepe et al., (2014) produced similar images of glass fibres used to reinforce concrete. It is true that glass fibres can be susceptible to surface modifications such as deposition and surface energy modification as written about in Cech *et al.*, (2002)

However, the FBGS used has a core of just 10µm alongside 125µm diameter of cladding, meaning that the sensing element is shielded considerably from outside effects. Not only this but the temperatures measured here are less than 1000°C and hence are unlikely to melt or effect glass.

5.4 Static Temperature Measurements

Static temperature measurements were conducted to observe the sensor's abilities to measure temperature change over time. Both sensors were able to measure temperature change over 1 minute without much drift.

Both thermocouples and fibre Bragg gratings were able to measure changes in thermal stability of the 1L/M, 10W

Although both sensors displayed higher temperature readings, at higher plasma powers, this significance of power increase was recorded differently across both sensors. In thermocouples, the two plasma conditions with the hottest temperatures were the conditions where the forward power was 15W.

The FBGS's highest temperatures however were from the plasmas recorded at lower flow rates of 1Lmin^{-1} . By contrast the thermocouples recorded the low flow rate jets as having a lower temperature than their lower flow rate counterparts.

Not only this, but the temperatures recorded by the thermocouples are considerably lower than those of the FBGS. The thermocouple measurements range from 88°C to 135°C while the FBGS ranged from 155°C to 730°C .

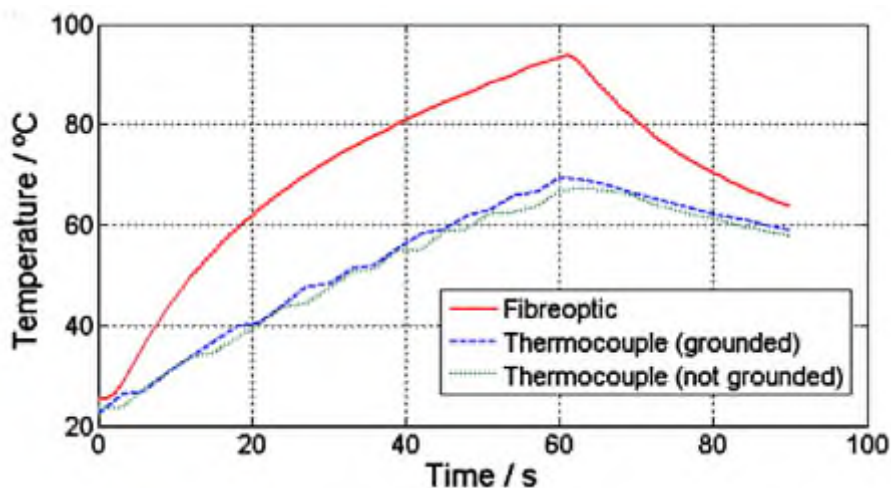


Figure 45 by Knoerzer et al., (2012) showing the temperature of a measured surface exposed to 1.55mbar pressure and 0.9kW microwave power by thermocouples and a fibre optic phosphor sensor

As previously mentioned, Knoerzer et al., (2012) found that thermocouples, both grounded and non-grounded, provided much lower temperature readings compared to a fibre optic sensor, as displayed in Figure 45.

In 5.1, the effect of flow rate on fibre Bragg grating sensing ability was discussed. The results and available literature indicate that fibre Bragg grating sensors should, by systematic error, read too high at higher flow rates. This is due to the strain effect on the sensor.

Thermocouples have been used as strain sensors in the past, although not through direct measurement, but by measuring temperature change across a set distance (Hung et al., 2005) (Karlsson et al., 2003).

A consideration could be the effect of the temperature of the thermocouple lowering the surrounding temperature (Honda and Iwamura, 2017). At lower flow rates this could be possible as the surrounding gas has more time cool to the thermocouple temperature. There could also be some effect from the surrounding air which is possibly less heated at lower flow rates.

Hashim, Aadim and Rustom (2017) measured the effect of flow rate on atmospheric 'cold' plasma temperature and electron density using optical emission spectroscopy (OES). The study showed that between 5 to 20 Lmin⁻¹ the electron temperature of the plasma decreased as the flow rate increase, supporting the results from the FBGS. They also discover an increase in electron density with the increase in flow rate.

OES was also utilised in the work of Humud, Abbas and Rauuf (2015) to measure electron and gas temperature. As with our experiment, they observed at atmospheric argon microwave plasma at 2.5GHz. They measured the effects of flow rates 1, 2.5 and 5 Lmin⁻¹ but with a much higher power of 850W.

The experiment also found that with an increase in flow rate, there was a subsequent increase in electron density with a decrease in electron temperature. An infrared thermometer was used to measure the gas temperature at different flow rates over time. A silicon wafer was heated by the torch flame until the temperature was perceived to equal that of the plasma. The infrared thermometer

then recorded the temperature over time. Here lower flow rates have shown to result in higher temperatures than higher flow rates.

Lindner et al., (2011) measured the temperature of inductively coupled plasmas, where an increase in flow rate also decreases temperature.

Mariotti et al., (2007) also used OES for low power (1-5W) micro plasma temperature measurements. Here they altered the power to measure the effect on gas and electron temperatures. Here gas temperatures were observed to increase with an increase in power, while electron temperature decreased.

They also altered the flow rate but at much smaller scales from 0.01Lmin^{-1} to 0.02L/min^{-1} . The flow rate change did not result in any noticeable difference in temperature, although this is likely due to the low flow rate variation being too small to show any noticeable change.

We know from simple experiments with a mercury thermometer that the gas temperature is likely to be much lower than from the results of the FBGS.

Anghel and Simon (2008) used a glass covered thermocouple to measure the temperature of an atmospheric helium plasma. Their results show a sharp increase in gas temperatures from 0.5 to 0.75Lmin^{-1} , then a slow decrease as flow rate increases from 1Lmin^{-1} to 5Lmin^{-1} . This is due to the volume of the plasma expanding and losing heat due to conduction and convection.

Spectral analysis of the plasma detected emission lines from molecular species other than helium. This is inevitable due to back diffusion of ambient air. It is possible this could have an effect on the temperature under atmospheric conditions. Particularly resulting in a much lower gas than electron temperature.

Likely in this case the FBGS is more accurately measuring plasma temperature, or providing an indication of electron temperatures rather than whole gas. The small sensor size coupled with the low thermal mass as discussed in 5.2 also supports this.

5.5 Z height Experiments

Although Z height effects were not particularly explored in this experiments, both sensors were tested to ensure they responded quickly to an increase in temperature, caused by a decrease in distance between the torch nozzle and the sensor. FBGSs showed quick response times at all z heights, while thermocouples showed a slightly longer response time, as stated in section 5.2.

Thermocouples also showed a sudden drop in temperature measurement at 2mm distance to the jet, with the temperature readings for 3mm and 2.5mms being almost equal. A drop of over 80°C in temperature was measured simply for increasing the Z height.

The thermocouple used was unshielded and not grounded. This is as to not disrupt the temperature measurement and induce noise. Literature as described in section 2.3.1 suggest thermocouples could be providing temperature readings much lower than what is correct, or simply inaccurate at closer z heights (Moon et al., 2002).

Corre et al., (2018) used FBGS and thermocouples to measure the temperature of plasma facing components in a long pulse tokomak. Here they have found the accuracy of the measurement to be about 10°C at low temperatures which matches results shown here [put this part in discussion] the response time of the sensor is 250ms +/- 50ms. They also found TC temperature results to be lower than that of the FBG sensor.

It is possible the effect of the electromagnetic field, combined with difficulties in heat transfer at high temperatures causes the thermocouple to provide inaccurate readings when within a plasma environment, particularly within a plasma jet.

5.6 Temperature Profiles

Once the viability of FBGS as an effective plasma device has been established, it is then evaluated as a method to characterise the temperature profile of the microwave plasma jet. Being able to characterise the jet with a physical sensor has advantages of spectroscopy as it could pin point temperature differences in a 'slice by slice' approach, being able to exactly pin point the location of a temperature reading.

Initial experiments using the FBGS struggled to acquire a profile without large amounts of noise. This is due to the unrestraint nature of the sensor, highlighting the need for restraint, as mentioned in section 5.1.

It is expected that the temperature distribution within the plasma jet to be Gaussian and hence the temperature profile to be normally distributed (Garg et al., 2008)

However it is observed that there is a slight skew to the results, where one side of the jet is significantly cooler than the other.

The most likely cause is the position of the extractor fan which is located behind and to the side of the plasma torch. As a result there is likely to be significant cooling at one side of both the x and Y axis, as well as movement of the beam towards the fan. This is observed particularly in Figure 41 where the effect of the fan causes a sharp temperature drop of 10°C.

The radio wave induced plasma did not display as much of an effect, however it is noted that the radiofrequency plasma has a full width half maximum of 18mm, in contrast to that of the microwave jet which is only 2mm. The results showed that the radiofrequency ranged from 300°C in the edge of the plasma, reaching 1000°C in the centre. Figure 44 displays a normally distributed curve, which could indicate that the thermal radio wave plasma is thermally Gaussian distributed.

6 Conclusions and future work

6.1 Conclusion

Fibre Bragg Grating sensors have shown to be accurate temperature sensors in the measurement of electromagnetic wave induced atmospheric plasma. They have been shown to have exceptionally fast response times and have the capability to detect temperature nearly independent of strain.

However the sensor lacks precision, as a likely cause of flow rate causing slight strain effects. The sensor shows temperature ranges of 10°C at 2mm z height, raising to 80°C at 101mm z height.

FBGS have shown to be unaffected by interference by the electromagnetic field and chemically reactive nature of some plasmas. Results show consistent temperature measurement across the lifetime of the fibre without drift in the Bragg wavelength. The chemically inert nature of glass reduces the effects of possible plasma etching or surface energy modification having an effect on the sensor's ability to measure.

Profiles have been characterised in both a microwave cool microplasma as well as within a thermal radiowave plasma, showing potential for fibre Bragg gratings to be used in the future as plasma temperature sensors, not only being able to measure temperature in a particular position of a plasma jet, but to also understand the temperature stability of the jet over time.

6.1.1 Future work

In order to improve the FBGS technology, additional mounting should be considered. A capillary glass tube surrounding the FBGS would improve the mechanical stability, reducing accidental breakage, and also shield the sensor from strain.

Another consideration should be to measure the temperature at a faster scanning rate to measure temperature changes over a couple of seconds. Ideally this would be at 2.5GHz to match that of the plasma frequency, however due to limitations of the interrogator, the fastest frequency possible is only 25 kHz. Never

the less, information regarding large temperature ranges found in measurement may be observed with higher frequency measurement.

Another future point would be to further ensure the calibration of the sensor through introduction of hot gas of known flow rate, at similar conditions, to the FBGS to ensure that the strain caused from flow rate does not have a greater effect at hotter temperatures than cooler ones. It would also be important to heat the sensor to 1000oC to determine if there is a need for further nonlinear calibration.

Finally, comparison with non-contact measurement devices such as pyrometer and OES would help to ensure that the temperature measurement is in line with other experiments.

7 REFERENCES

Ahamed S V 2013 Optical Fiber in Modern Networks *Intelligent Networks* 93–106 Online:

<https://www.sciencedirect.com/science/article/pii/B9780124166301000054>

Amiel S, Loarer T, Pocheau C, Roche H, Aumeunier M H, Gauthier E, Niliot C L and Rigollet F 2012 Surface temperature measurement of plasma facing components with active pyrometry *Journal of Physics: Conference Series* **395** 012074

Amos S U 2018 Cross sensitivity analysis of optical fibre-based sensing for high pressure, high temperature measurement in oil and gas applications. *Rgu.ac.uk* Online: <https://openair.rgu.ac.uk/handle/10059/3401>

Anghel S D and Simon A 2008 Preliminary investigations of a very low power atmospheric pressure Helium plasma *Romanian Journal of Physics* **55** 185–93

Anghel S D, Simon A and Frentiu T 2008 Spectroscopic investigations on a low power atmospheric pressure capacitively coupled helium plasma *Plasma Sources Science and Technology* **17** 045016

Anon 2009 Tufnol grades 6G/92 | SRBGF | Machined components | polyimide resin laminated plastic *Tufnol.com* Online: <https://www.tufnol.com/materials-full/glass-fabric-grades/tufnol-grade-6g-92.aspx>

Anon 2016 General Engineering and Science *Standard Handbook of Petroleum and Natural Gas Engineering* 2-1-2–177 Online: <https://www.sciencedirect.com/science/article/pii/B9780123838469000023>

Anon 2019 Students research cleaning solar collectors without water *Cranfield.ac.uk* Online: <https://www.cranfield.ac.uk/press/news-2019/students-research-cleaning-solar-collectors-without-water>

Arie A, Lissak B and Tur M 1999 Static fiber-Bragg grating strain sensing using frequency-locked lasers *Journal of Lightwave Technology* **17** 1849–55

Bashour R 2016 High voltage optical fibre sensor for use in wire relay electrical protection systems *Ethos.bl.uk* Online:

<https://ethos.bl.uk/OrderDetails.do?did=12&uin=uk.bl.ethos.705066>

Cao Z 2010 *Large-scale Spatially Extended Atmospheric Pressure Plasma*

Chehura E, James S W and Tatam R P 2007 Temperature and strain discrimination using a single tilted fibre Bragg grating *Optics Communications* **275** 344–7

Chen D, Huo L, Li H and Song G 2018 A Fiber Bragg Grating (FBG)-Enabled Smart Washer for Bolt Pre-Load Measurement: Design, Analysis, Calibration, and Experimental Validation *Sensors* **18** 2586 Online:

<https://www.mdpi.com/1424-8220/18/8/2586/htm>

Chen F F and Chang J P 2003 Langmuir Probes *Lecture Notes on Principles of Plasma Processing* 79–93 Online:

https://link.springer.com/chapter/10.1007/978-1-4615-0181-7_12

Corning 2012 *MACOR® Machinable Glass Ceramic For Industrial Applications* Online:

<https://www.corning.com/media/worldwide/csm/documents/71759a443535431395eb34ebead091cb.pdf>

Corre Y, Laffont G, Pocheau C, Cotillard R, Gaspar J, Roussel N, Firdaouss M, Gardarein J-L, Guilhem D and Missirlian M 2018 Integration of fiber Bragg grating temperature sensors in plasma facing components of the WEST tokamak *Review of Scientific Instruments* **89** 063508

Cusano A, Cutolo A and Giordano M 2019 Fiber Bragg Gratings Evanescent Wave Sensors: A View Back and Recent Advancements *Lecture Notes Electrical Engineering* 113–52 Online:

https://link.springer.com/chapter/10.1007/978-3-540-69033-7_7

Duan Y, Huang C and Yu Q 2005 Low-temperature direct current glow discharges at atmospheric pressure *IEEE Transactions on Plasma Science* **33** 328–9

Faraday M 1845 *The Manuscripts of Michael Faraday (1791-1867)* (Wakefield: Microform Academic Publishers, [200])

Farias C E, Bernardelli E A, Borges P C and Mafra M 2017 Determination of Surface Temperature in ICP RF Plasma Treatments of Organic Materials *Materials Research* **20** 1432–43

Freeman D E and Auer J A 2012 Instrument Preparation, Sterilization, and Antiseptics *Equine Surgery* 98–111 Online:
<https://www.sciencedirect.com/science/article/pii/B9781437708677000090>

Garg R K, Anderson T N, Lucht R P, Fisher T S and Gore J P 2008 Gas temperature measurements in a microwave plasma by optical emission spectroscopy under single-wall carbon nanotube growth conditions *Journal of Physics D: Applied Physics* **41** 095206

Ghosh C, Alfred Q and Ghosh B 2015 Spectral Characteristics of Uniform Fiber Bragg grating with different grating length and refractive index variation *International Journal of Innovative Research in Computer and Communication Engineering* **3**

Giallorenzi T, Bucaro J, Dandridge A, Sigel G, Cole J, Rashleigh S and Priest R 1982 Optical fiber sensor technology *IEEE Journal of Quantum Electronics* **18** 626–65

Grattan K T V 1995 Fiber optic techniques for temperature measurement *Optical Fiber Sensor Technology* 441–59 Online:
https://link.springer.com/chapter/10.1007%2F978-94-011-1210-9_15

Güemes A and Messervey T B 2010 Smart textile and polymer fibres for structural health monitoring *Textiles, Polymers and Composites for Buildings* 330–50

Güemes A and Messervey T B 2010 Smart textile and polymer fibres for structural health monitoring *Textiles, Polymers and Composites for Buildings* 330–50 Online:
<https://www.sciencedirect.com/science/article/pii/B978184569397850011X>

Hashim I, Aadim K and Rustom M 2017 Atmospheric cold plasma, plasma jet
Iraqi Journal of Physics **15** 117–24

Hendow S T 1997 Optical Materials and Devices *Experimental Methods in the Physical Sciences* 343–67 Online:
<https://www.sciencedirect.com/science/article/pii/S0076695X08606213>

Hirayama N and Sano Y 2000 Fiber Bragg grating temperature sensor for practical use *ISA Transactions* **39** 169–73

Honda S and Iwamura T 2017 Analysis of Heat Transfer in Thermocouples Immersed in High Temperature Gas with Short Insertion Length *SICE Journal of Control, Measurement, and System Integration* **10** 282–7

Humud H, Abbas Q and Rauuf A 2015 *Effect of Gas Flow Rate on The Electron Temperature, Electron Density and Gas temperature for Atmospheric Microwave Plasma Jet*

Hung P C, Irwin G, Kee R and McLoone S 2005 Difference equation approach to two-thermocouple sensor characterization in constant velocity flow environments *Review of Scientific Instruments* **76** 024902

Jakubowski N, Prohaska T, Vanhaecke F, Roos P H and Lindemann T 2011 Inductively coupled plasma- and glow discharge plasma-sector field mass spectrometry : Part II. Applications *Journal of Analytical Atomic Spectrometry* **26** 727

Jeon S M and Kim Y P 2004 Temperature measurements using fiber optic polarization interferometer *Optics & Laser Technology* **36** 181–5

Jessner A 2010 *PLASMA PHYSICS FOR ASTRONOMERS* Online:
http://www3.mpifr-bonn.mpg.de/old_mpifr/imprs/bbl/bbl_downloads/jessner/Plasma%20Physics%20for%20Astronomers.pdf

Kanazawa S, Kogoma M, Moriwaki T and Okazaki S 1988 Stable glow plasma at atmospheric pressure *Journal of Physics D: Applied Physics* **21** 838–40

Karlsson J K-H, Morén M, Jonsson B, Tomani H and Bergdahl B-G 2003 Flow measurements by noise analysis of thermocouple signals from the BOCA experiment at the Studsvik R2 reactor *Progress in Nuclear Energy* **43** 289–96

Kefford B 2019 British Library EThOS - Search and order theses online *Ethos.bl.uk* Online:

<https://ethos.bl.uk/OrderDetails.do?did=10&uin=uk.bl.ethos.704777>

Khan I and Ahmed I 2012 Sensing Principle Analysis of FBG Based Sensors *IOSR Journal of Electrical and Electronics Engineering* **1** 01–6 Online:

<http://www.iosrjournals.org/iosr-jeee/Papers/vol1-issue3/A0130106.pdf?id=2693>

Knoerzer K, Murphy A B, Fresewinkel M, Sanguansri P and Coventry J 2012 Evaluation of methods for determining food surface temperature in the presence of low-pressure cool plasma *Innovative Food Science & Emerging Technologies* **15** 23–30

Lieberman M A and Lichtenberg A J 2005 *Principles of plasma discharges and materials processing* (Hoboken, N.J.: Wiley-Interscience)

Lindner H, Murtazin A, Groh S, Niemax K and Bogaerts A 2011 Simulation and Experimental Studies on Plasma Temperature, Flow Velocity, and Injector Diameter Effects for an Inductively Coupled Plasma *Analytical Chemistry* **83** 9260–6

Liu C 2019 Advanced optical fibre grating sensors for biochemical applications *Ethos.bl.uk* Online:

<https://ethos.bl.uk/OrderDetails.do?did=1&uin=uk.bl.ethos.767441>

Lu P and Chen Q 2008 Fiber Bragg grating sensor for simultaneous measurement of flow rate and direction *Measurement Science and Technology* **19** 125302

Mariotti D, Shimizu Y, Sasaki T and Koshizaki N 2007 Gas temperature and electron temperature measurements by emission spectroscopy for an atmospheric microplasma *Journal of Applied Physics* **101** 013307

Mc Cullagh J J, Setchell D J, Gulabivala K, Hussey D L, Biagioni P, Lamey P J and Bailey G 2000 A comparison of thermocouple and infrared thermographic analysis of temperature rise on the root surface during the continuous wave of condensation technique *International endodontic journal* **33** 326–32 Online: <https://www.ncbi.nlm.nih.gov/pubmed/11307207>

Medlock R S 1987 Fibre Optic Intensity Modulated Sensors *Optical Fiber Sensors* 131–42 Online: https://link.springer.com/chapter/10.1007/978-94-009-3611-9_6

Mindlin R 1939 A Review of the Photoelastic Method of Stress Analysis. II: Journal of Applied Physics: Vol 10, No 5 *Journal of Applied Physics* Online: 10

Misra N N, Schlüter O and Cullen P J 2016 Plasma in Food and Agriculture *Cold Plasma in Food and Agriculture* 1–16 Online: <https://www.sciencedirect.com/science/article/pii/B9780128013656000019>

Miura N 2011 Magneto-Spectroscopy of Semiconductors *Comprehensive Semiconductor Science and Technology* 256–342 Online: <https://www.sciencedirect.com/science/article/pii/B9780444531537000857>

Moon S Y, Choe W, Uhm H S, Hwang Y S and Choi J J 2002 Characteristics of an atmospheric microwave-induced plasma generated in ambient air by an argon discharge excited in an open-ended dielectric discharge tube *Physics of Plasmas* **9** 4045–51

Morris A S and Langari R 2016 Temperature Measurement *Measurement and Instrumentation* 407–61 Online: <https://www.sciencedirect.com/science/article/pii/B9780128008843000149>

Niemira B A 2012 Cold Plasma Decontamination of Foods *Annual Review of Food Science and Technology* **3** 125–42

Niewczas, P, Fusiek, G, Lescure, C, Johnson, M, Ivings, E, West, A, Crolla, P and Walsh, M 2008 Concept level evaluation of the full-scale deployment of fibre Bragg grating sensors for measuring forces in JET during plasma

disruption events *Fifth International Conference on Condition Monitoring and Machine Failure Prevention Technologies*

O'Kane D F and Mittal K L 1974 Plasma cleaning of metal surfaces *Journal of Vacuum Science and Technology* **11** 567–9 Online:
<https://avs.scitation.org/doi/10.1116/1.1318069>

Othonos A and Kalli K 1999 *Fiber bragg gratings : fundamentals and applications in telecommunications and sensing* (Boston ; London: Artech House, Cop) Online: <https://lib.ugent.be/en/catalog/rug01:000800781>

Polyak J 2008 *Psg teflon ptfe* Online:
http://catalog.wshampshire.com/Asset/psg_teflon_ptfe.pdf

Raizer Y 1991 *Gas Discharge Physics* (New York: Springer-Verlag) Online:
[https://www.scirp.org/\(S\(i43dyn45teexjx455qlt3d2q\)\)/reference/ReferencesPapers.aspx?ReferenceID=1622876](https://www.scirp.org/(S(i43dyn45teexjx455qlt3d2q))/reference/ReferencesPapers.aspx?ReferenceID=1622876)

Reference list

Reference list

Rogers A J 1977 Optical methods for measurement of voltage and current on power systems *Optics & Laser Technology* **9** 273–83

Roth J R 1995 *Industrial plasma engineering* vol 1 (Bristol: Institute Of Physics Publishing)

Ruddy M J 1975 *Temperature measurements in an argon plasma jet* (University of Leicester) Online:
<https://ethos.bl.uk/OrderDetails.do?did=2&uin=uk.bl.ethos.471150>

Rusby R 2016 *Good Practice Guide No. 125. Introduction to Temperature Measurement* ed National Physical Laboratory (London: Queen's Printer and Controller of HMSO)

Sheng Q, Liu G, Reinke M L and Han M 2018 A fiber-optic bolometer based on a high-finesse silicon Fabry-Pérot interferometer *Review of Scientific Instruments* **89** 065002

Sillanpää M and Shestakova M 2017 Emerging and Combined Electrochemical Methods *Electrochemical Water Treatment Methods* 131–225 Online: <https://www.sciencedirect.com/science/article/pii/B9780128114629000037>

Slepukhov A V 2018 An overview of use of fiber-optical sensors in oil and gas industry *Automation, Telemechanization and Communication in Oil Industry* 5–10

Spillman W B 1982 Multimode fiber-optic pressure sensor based on the photoelastic effect *Optics Letters* **7** 388 Online: <https://www.osapublishing.org/ol/viewmedia.cfm?uri=ol-7-8-388&seq=0>

Spitzer L 1956 *Physics of fully ionized gases* (London: Interscience Publishers Ltd)

Sturrock P A 1994 *Plasma physics : an introduction to the theory of astrophysical, geophysical, and laboratory plasmas* (Cambridge: Cambridge University Press)

Suresh R, Tjin S and Hao J 2012 Fibre Bragg Gratings *Smart Materials in Structural Health Monitoring, Control and Biomechanics* (Delhi: SpringerLink) pp 413–39 Online: <https://link.springer.com/content/pdf/10.1007%2F978-3-642-24463-6.pdf>

Talyanskii V L 1992 The instability of surface plasma vibrations in resonant tunneling diodes (RTD) *Solid State Communications* **81** 643–4 Online: <https://www.sciencedirect.com/science/article/pii/003810989290611C>

Taylor P R and Pirzada S A 1994 Thermal plasma processing of materials: A review *Advanced Performance Materials* **1** 35–50

The College of Saint Benedict and Saint John's University 5: *Langmuir's Probe* Online: http://www.physics.csbsju.edu/370/langmuir_probe.pdf

The plastics shop (2019) *GRADE 6F/45 TUFNOL TECHNICAL DATA and PHYSICAL PROPERTIES for TUFNOL Grade 6F/45 Sheet: PROPERTY TYPICAL RESULT* Online:

https://www.theplasticshop.co.uk/plastic_technical_data_sheets/tufnol_6F45_technical_data_sheet.pdf

Thompson W 1962 *An Introduction to Plasma Physics* (Oxford: Pergamon Press)

TKACHENKO N V 2006 Optics and Optical Devices *Optical Spectroscopy* 15–38 Online:

<https://www.sciencedirect.com/science/article/pii/B9780444521262500265>

Tonks L and Langmuir I 1929 Oscillations in Ionized Gases *Physical Review* **33** 195–210 Online: <https://journals.aps.org/pr/abstract/10.1103/PhysRev.33.195>

Ulises F 2018 Optical fibre sensors for novel medical devices during anaesthesia - Nottingham ePrints *Nottingham.ac.uk*

van Gessel A F H, Hrycak B, Jasiński M, Mizeraczyk J, van der Mullen J J A M and Bruggeman P J 2013 Temperature and NO density measurements by LIF and OES on an atmospheric pressure plasma jet *Journal of Physics D: Applied Physics* **46** 095201

Venkatesan V, Ramalingam R, Yamashita S, Kashiwagi K and Costa J 2017 *Frequency-Shifted Mgth Fiber Bragg Grating Laser Sensor Recent citations Macrobending SMultiwavelenS fiber-optic anemometer and flow sensor*

Wang A, He S, Fang X, Jin X and Lin J 1992 Optical fiber pressure sensor based on photoelasticity and its application *Journal of Lightwave Technology* **10** 1466–72 Online:

<https://pdfs.semanticscholar.org/6bb2/91e7e6d93a542bb7bfdb029c1630e245eb70.pdf>

Weimer W A, Cerio F M and Johnson C E 1991 Examination of the chemistry involved in microwave plasma assisted chemical vapor deposition of diamond *Journal of Materials Research* **6** 2134–44

Wiesemann K *A Short Introduction to Plasma Physics* Online: <https://arxiv.org/ftp/arxiv/papers/1404/1404.0509.pdf>

Wilkinson C D W and Rahman M 2004 Dry etching and sputtering ed M W Thompson, J S Colligon and R Smith *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* **362** 125–38 Online:

<https://pdfs.semanticscholar.org/fdee/ae74948e247213ff0db46c086053e35edb8f.pdf>

Wolf R and Sparavigna A C 2010 Role of Plasma Surface Treatments on Wetting and Adhesion *Engineering* **02** 397–402 Online:

https://file.scirp.org/pdf/Engineering20100600011_80451114.pdf

Wuilloud J C ., Wuilloud R G, Vonderheide A P and Caruso J A 2004 Gas chromatography/plasma spectrometry—an important analytical tool for elemental speciation studies *Spectrochimica Acta Part B: Atomic Spectroscopy* **59** 755–92

Yoshida T 1990 *Combustion and plasma synthesis of synthesis of high temperature materials* (New York: VCH)

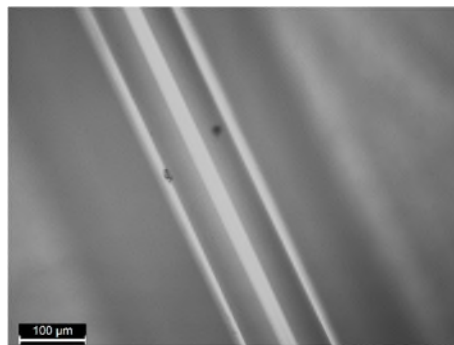
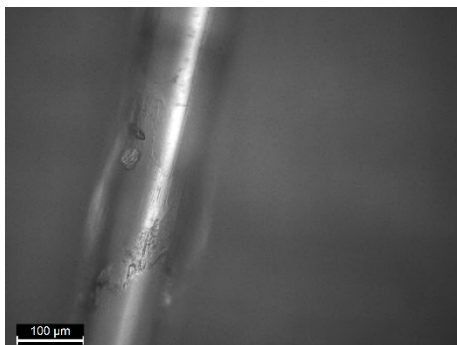
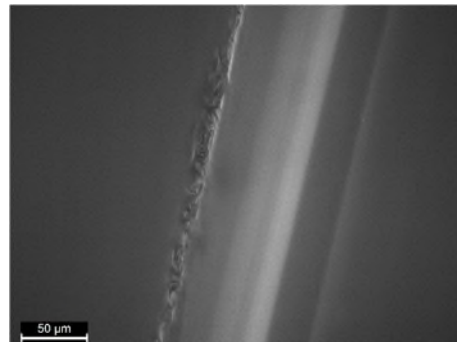
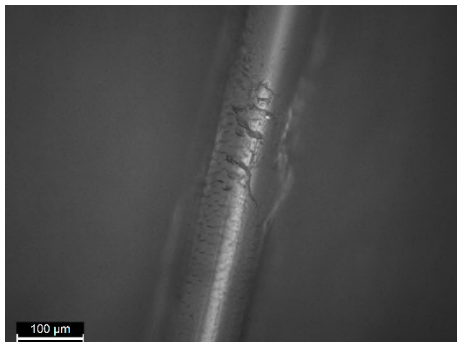
Zhang C 2012 Fibre Bragg gratings in polymer optical fibre for applications in sensing *Ethos.bl.uk* Online:

<https://ethos.bl.uk/OrderDetails.do?did=1&uin=uk.bl.ethos.558221>

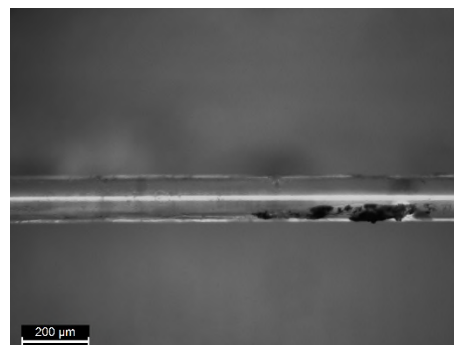
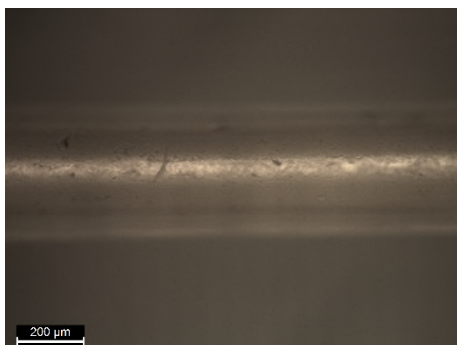
APPENDICES

Appendix A Fibre Bragg grating images

A.1 Before Plasma temperature measurement



A.2 After Temperature measurement



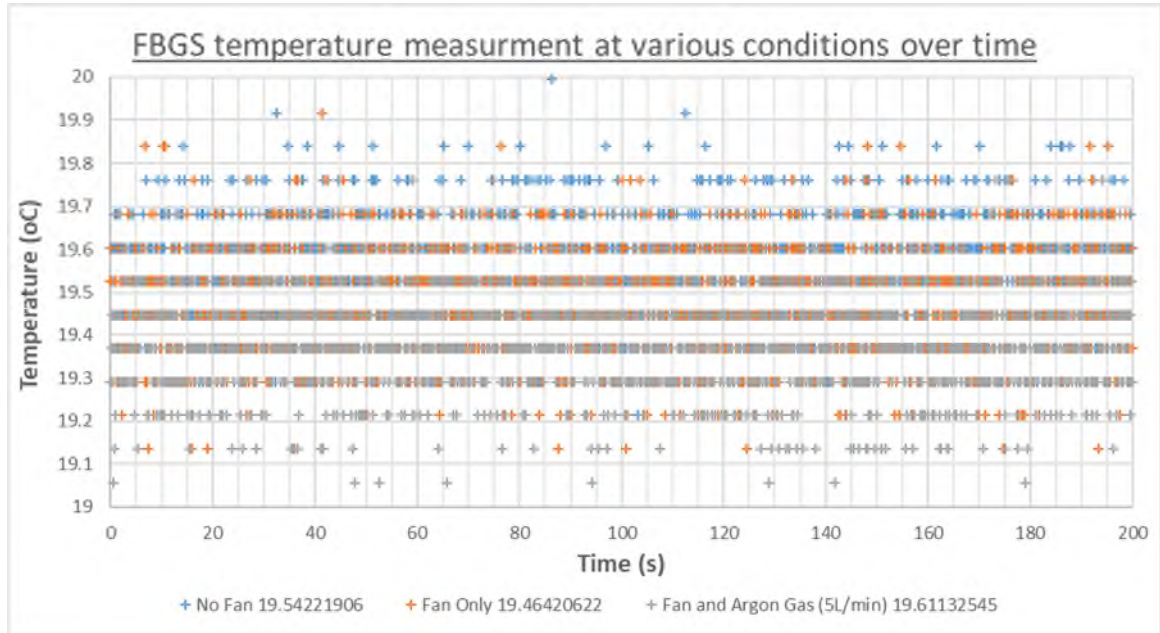
Appendix B

CCI measurement photo



Appendix C

C.1 FBGS temperature measurement



The above graph displays the difference between FBGS measurement in ambient air with and without effect of the extractor fan. These measurements were compared with measurements of ambient temperature argon gas in the centre of gas flow diameter at 5L/min over time.

Appendix D

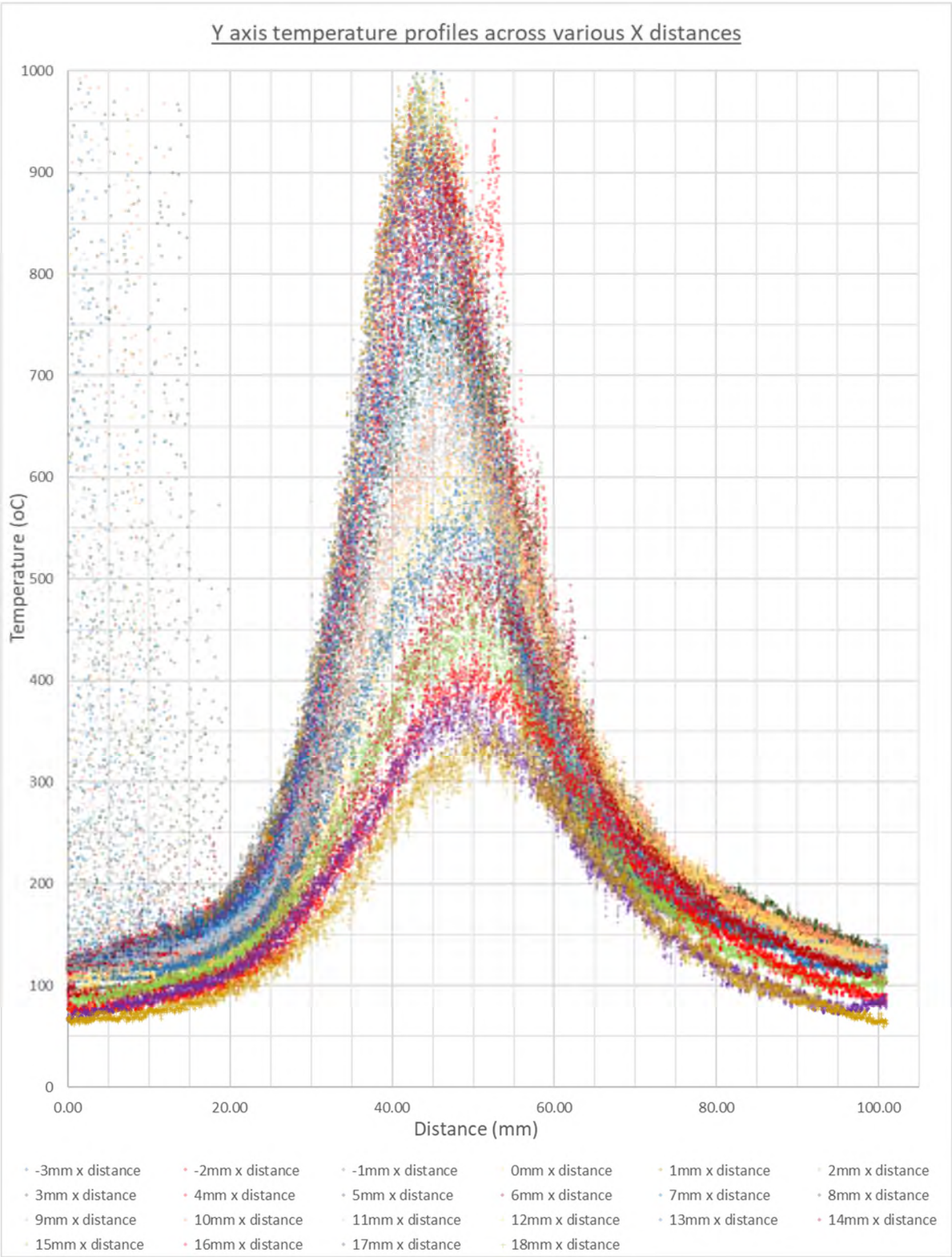


Figure displays the Y axis temperature profiles, across 22 X axis positions ranging from -3mm to +18mm from the centre of the jet. Some interference from

strain can be observed between 0 to 20mm distance and around the centre of the jet. This is likely a result of the high flow jet dislodging the fibre from its mounting.