

CRANFIELD UNIVERSITY

SHAFAYAT HASAN CHOWDHURY

AN EXPERIMENTAL INVESTIGATION OF A FULL-SCALE AIRCRAFT ECS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD

Academic Year: 2021 - 2022

Supervisor: Professor Ian K. Jennions
Associate Supervisor: Dr Fakhre Ali

April 2022

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ABSTRACT

Aircraft Environmental Control System (ECS) conditions hot bleed air and regulates to the cockpit, cabin and avionics bay. It consists of multiple subsystems which are prone to degradation and eventually failure. There has been a number of incidents reported of sudden cabin pressure loss resulting in emergency landing. Such incidents at high altitudes can be problematic. Furthermore, the ECS has been reported to be a major driver for unscheduled maintenance impacting the operating costs. The development of an accurate diagnostic solution would identify the degradation early, hence, ensuring safety and reduction in maintenance costs. Researchers in the past have adequately studied model-based diagnostic techniques for the ECS at a component level. However, the ECS being an integrated system, the interdependencies between components makes the diagnosis difficult, particularly when the valves within the ECS masks fault occurrences and the fault propagates through the system. For this reason, IVHM centre has developed an ECS simulation model, SESAC, which has the capability to perform healthy and component degradation simulation. This PhD focuses on an experimental investigation on the ECS to facilitate verification of SESAC. A novel ground test facility (GTF) is developed on a Boeing 737-400 aircraft. The GTF is used to produce data under different ambient and operating conditions, which is used for PACK performance analysis. The importance of appropriate design of control system for ECS simulation model has been highlighted in this research. Furthermore, aircraft data has been used to provide understanding of the ECS control system. The control logic within SESAC has been fine-tuned to support heat exchanger degradation and valve malfunction simulation studies have been conducted. The ability of the 737-GTF to capture fault occurrence has also been demonstrated using experimental data.

Keywords:

Air Conditioning System; Condition Monitoring; Verification and Validation; Fault Detection; Control System

Praise be to Allah (swt)

Dedicating this work to my beloved parents for whom I got to experience this journey and to my wife who supported me with all her love and strength.

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Special thanks to the Boeing company for funding and supporting throughout this project. I would also like to thank Monarch Engineering Services LTD and Cranfield University Gas-Turbine Laboratory for helping me with setting up the GTF. Thanks to Cengiz Turkuglo for all the support with the B737-400.

I am forever grateful to my loving wife, Nafisa Insan, for always being there for me, enduring all the pain and supporting me through the difficult times. Most importantly for all the love she gives me every day.

Although I always dreamt of doing a PhD, I never thought I would make it. Without all the sacrifices my father made for me - the financial struggles, being my friend, understanding me, loving me, for him to grow only to give me a better future – I would have been lost in the crowd. He always provided me the best possible comfort and motivated me to strive for excellence despite the difficulties I faced during my school days and beyond.

A special note to my dad -

‘Baba, thanks for always believing in me. Whoever I am today is only because of Almighty Allah and you.’

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LIST OF ABBREVIATIONS

ACM	Air Cycle Machine
ADS	Air Distribution System
Alt	Altitude
ANN	Artificial Neural Network
APU	Auxiliary Power Unit
B737	Boeing 737
BAS	Bleed Air System
BFSL	Best Fit Straight Line
CBM	Condition Based Maintenance
CHX	Condensing Heat Exchanger
CMP	Compressor
DAQ	Data Acquisition Unit
DNN	Deep Neural Network
DS	Degradation Severity
DT	Digital Twin
ECS	Environmental Control System
EKF	Extended Kalman Filter
FLECS	Functional Model Library of the Environmental Control System
FSS	Full-Scale Span
GTF	Ground Test Facility

HPWS	High Pressure Water Separator
k-NN	k-Nearest Neighbor
LC	Load Condition
MSA	Multivariate Statistical Analysis
PACK/PCK	Passenger Air Conditioner
PCA	Principal Component Analysis
PID	Proportional-Integral-Derivative
pTCV	Post TCV
PV	PACK Valve
PHX	Primary Heat Exchanger
Ram	Ram- ambient air
RC	Reference Case
RH	Relative Humidity
RHX	Reheating Heat Exchanger
RUL	Remaining Useful Life
SESAC	Simscape ECS Simulation under All Conditions
SH	Specific Humidity
SHX	Secondary Heat Exchanger
Std.Dev.	Standard Deviation
STF	Strong Tracking Filter
SVM	Support Vector Machine
TCV	Temperature Control Valve

TRB	Turbine
V&V	Verification and Validation
WS	Water Separator

LIST OF SYMBOLS

A	Area
D_H	Hydraulic diameter
f	Friction factor
k	Loss coefficient
L	Length
$\dot{m}$	Mass Flow
P	Pressure
T	Temperature
$\hat{T}$	Simulation Output Temperature
u	Amplifies Mass Flow Error
$\hat{u}$	Control Command
v	Velocity
Y	PACK Valve Angle Output

LIST OF SUBSCRIPTS

0	Initial Condition
amb	Ambient
Cab	Cabin
c	Cold
d	Dynamic
h	Hot
<i>i</i>	Inlet
<i>o</i>	Outlet
PR	Pressure Ratio
pri	Primary
w	Wall
s	Static
sec	Secondary
t	Total

LIST OF GREEK SYMBOLS

α	Model Parameter
β	Model Parameter
δ	Uncertainty Error
ϵ	Effectiveness
μ	Mean Value
ρ	Density
σ	Standard Deviation
τ	Shear stress

1 Introduction

“Once you have tasted flight, you will forever walk the earth with your eyes turned skyward, for there you have been, and there you will always long to return.”

- Leonardo Da Vinci

1.1 Motivation behind this research

The aviation industry is constantly evolving with the advancement in technology. One of the greatest dreams of mankind was the ability to fly. Since the Wright brother made four brief flights with the first powered aircraft in 1903, the aviation industry has come a long way in the last hundred years [1]. According to an article published by the Civil Aviation Authority (CAA) [2], the air transportation mode is considered to be safer than any others. To maintain this level of safety assurance, the aviation industry is focusing a lot more on their maintenance, repair, and overhaul business sector. In doing so, the maintenance cost per year has been reported to be 31 billion US dollars [3]. Integrated Vehicle Health Management (IVHM) technology has been introduced to minimise the maintenance cost, whilst ensuring safety of the fleet, allowing fault detection and isolation through condition monitoring of multiple components within a system [4].

The Boeing Company, funding body of this study, has reported the aircraft Environmental Control System (ECS) of the legacy aircraft Boeing 737 to be a major driver for maintenance [5]. The aircraft ECS conditions bleed air to be distributed in the cockpit, cabin, and avionics bay. Within the Passenger Air Conditioner (PACK), a sub-system of the ECS, the temperature, pressure and the humidity of the air is regulated to desired levels. To deliver these requirements the PACK is made up of multiple components which are all prone to degradation through its life cycle, and eventually failure. There have been multiple incidents reported [6–9], where a sudden loss of cabin pressure resulted in an emergency

landing of the aircraft. The root cause analysis suggested that the PACK protection system ceased PACK functionality due to fault occurrence.

The legacy aircraft such the Boeing 737, are not well instrumented with sensors that can generate data to be used for diagnostic purposes. The lack of sensors, and also unavailability of data, hinders the study of health indicating parameters of the critical components such as the heat exchangers (HX), valves, air-cycle machine (ACM) and water separator (WS). Analysis of the health indicating parameters could provide early warning of system failure, hence help in preventing incidents mentioned earlier. Research suggests there is a compelling need to acquire comprehensive set of data from the ECS to perform system performance characteristics analysis and verification and validation (V&V) of the IVHM technology to be used for fault detection and isolation [10]. In light of that, this PhD focuses on developing a 737 Ground Test Facility (GTF) to enable PACK performance analysis using acquired experimental data.

1.2 Environmental Control System (ECS)

The ECS of an aircraft provides conditioned air to the cockpit, cabin and avionics bay. It maintains the cabin pressurisation and regulates air temperature and humidity [11]. The ECS consists of 3 primary subsystems that helps achieving the target conditions: (i) Bleed Air System (BAS), (ii) PACK and (iii) Air Distribution System (ADS). Figure 1-1 shows a generic ECS architecture which shows the links between the subsystems within the ECS.

The BAS provides the pressurised air to the PACK for conditioning. Part of the bleed mass flow, before entering the PACK, is taken out to drive the ram turbofan to drive cold ambient air over the heat exchangers in the PACK to enable pre-cooling of the bleed air. After conditioning of the bleed air in the PACK, the air is mixed with trim and recirculating air from the cabin in the mixing manifold before it is distributed to different zones of the aircraft. The subsystems are briefly discussed below; however, the PhD is focused on the PACK.

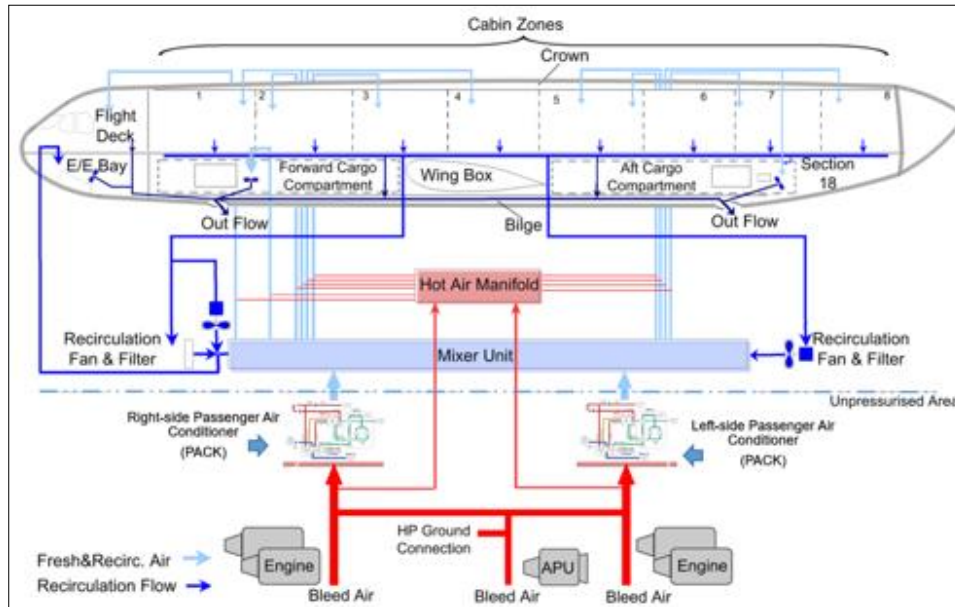


Figure 1-1 ECS schematic [12]

1.2.1 Bleed Air System (BAS)

The BAS provides pressurised air to the ECS system. It also drives the ram turbofan and provides hot bleed air to the anti-ice system. Figure 1-2 shows a typical engine BAS schematic. The BAS uses valves and ducts to bleed air from the compressor section of the engine and Auxiliary Power Unit (APU). The extracted air is usually at a temperature of approximately 200°C and a pressure of approximately 275kPa depending on the engine type and compressor stage at which the air is bled from [13]. The hot bleed air is used for a number of reasons including, air conditioning, engine start (APU bleed air), and wing and engine anti-ice systems.

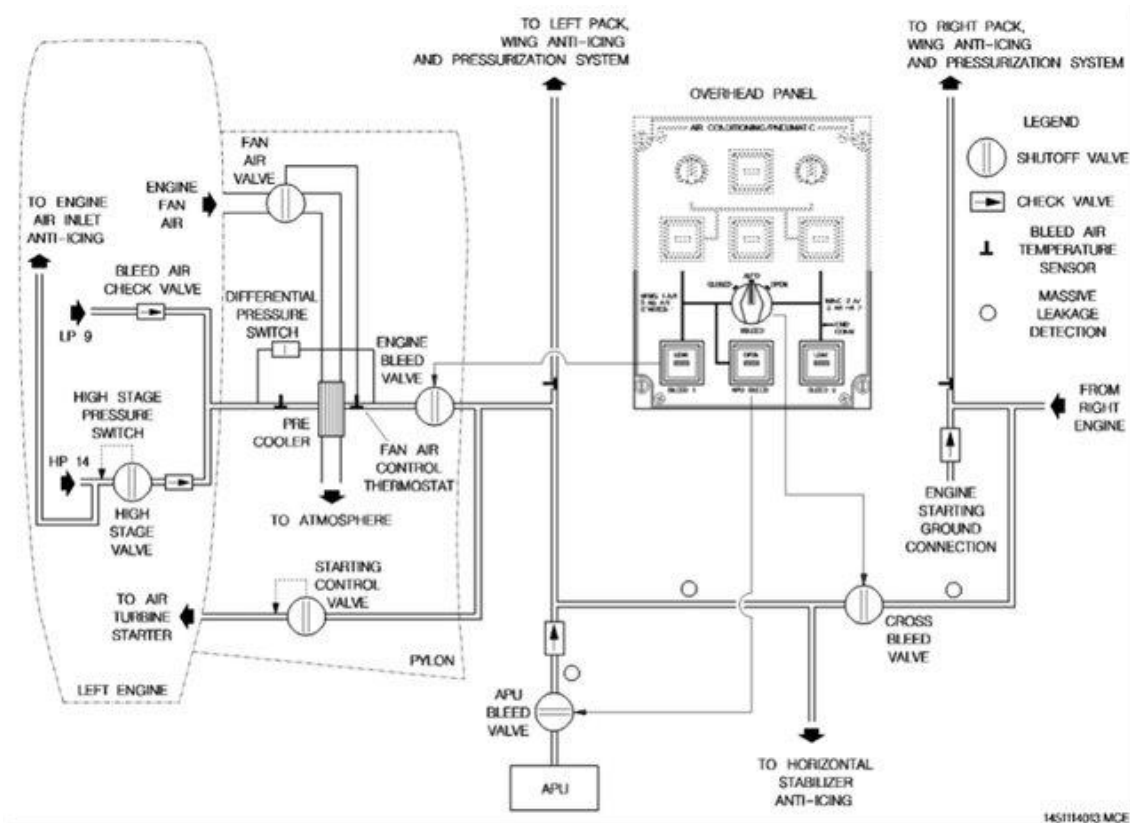


Figure 1-2 Example of a Bleed Air System [14]

1.2.2 Passenger Air Conditioner

The PACK is the primary system for conditioning the airflow within the ECS. Figure 1-3 illustrates the schematic of a single PACK with High-Pressure Water Separator (HPWS) in a B737-400 aircraft. It consists of Valves, Heat Exchangers, an ACM and a HPWS. There are other ECS systems, such as electrically driven ECS (used in modern aircraft) [15, p.3], pneumatic ECS with low-pressure water separator (LPWS) (generally used in older generation aircraft) [16], vapour cycle ECS (used for light turboprop aircraft application) [17] and membrane-based dehumidifier (used in spacecraft) [18].

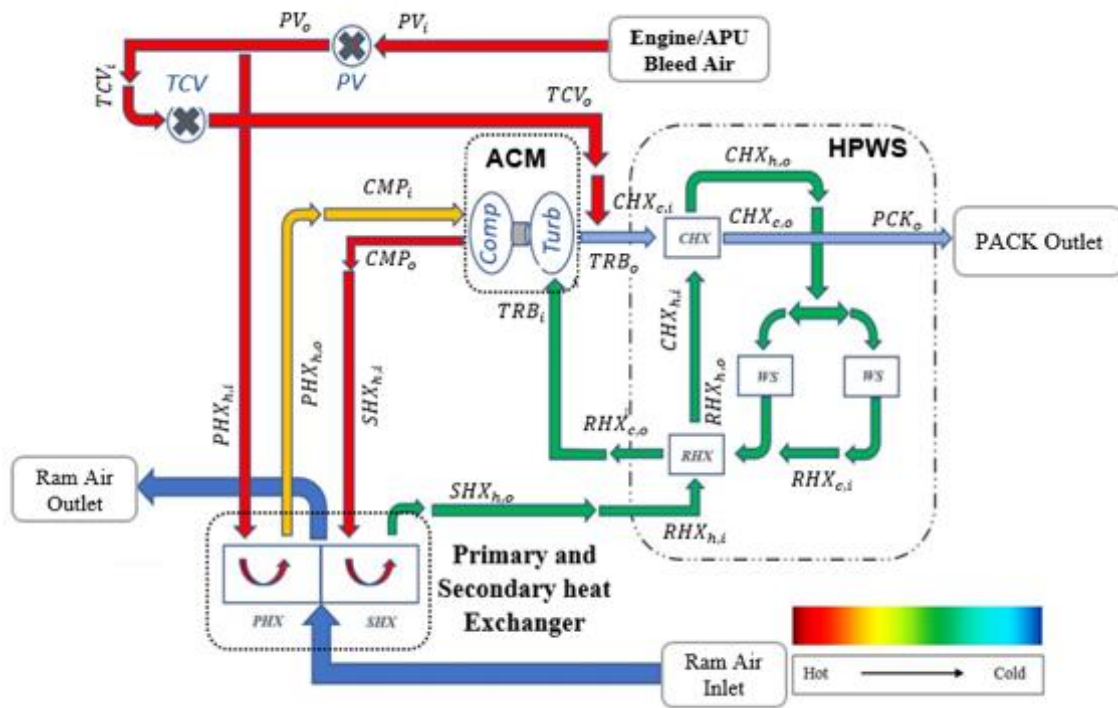


Figure 1-3 B737-400 PACK schematic (labelling has been modified to align with this thesis) [12]

Following the sequence shown in Figure 1-3, the PACK receives bleed air at high temperature and pressure, primary cooling takes place in the Primary Heat Exchanger (PHX), and secondary cooling takes place in the Secondary Heat Exchanger (SHX), after the flow is compressed. Cold Ram air, which originates from outside the aircraft, flows through the Ram air duct and, after being used as a heat sink for PHX and SHX, is deposited back into the aircraft's airstream. After the SHX the temperature of the bleed air has been substantially reduced and the high pressure flow is expanded through a turbine, after passing through the HPWS to control humidity. At the outlet of the turbine the air temperature can potentially drop below freezing and, if this occurs, it is addressed by mixing in part of the bypass hot bleed flow through the Temperature Control Valve (TCV). The mixing of this air is controlled in order to match the PACK outlet temperature against the cabin demand.

1.2.3 Air Distribution System

As illustrated in Figure 1-4, the function of the trim system is to ensure the supply of hot air to the cabin air distribution ducts. This allows the adjustment in the temperature supplied to each cabin compartment. For example, both forward and aft can be set to meet 24°C temperature demand, however, depending on the heat load of each compartment, the required temperature supply can vary in order to meet the demanded temperature. In Boeing 737-400 a small proportion of the mass flow going into the PACK core is used to fulfil the function of the trim valve. Switching on the trim system would therefore allow the PACK-zone controller to regulate (open or close) the trim valve based on the cabin temperature sensor feedback. The amount of mass flow going through the core of the PACK is therefore strongly dependant on the status of the trim valve, which can consequently affect the performance characteristics of the components mounted within the core of the PACK i.e. PHX, SHX, ACM, HPWS. The trim flow is mixed at the mixing manifold with the conditioned air from the PACK and recirculating air from the cabin. The trim system and its impact on PACK performance has been identified during this PhD study and is discussed in detail in Chapter 4.

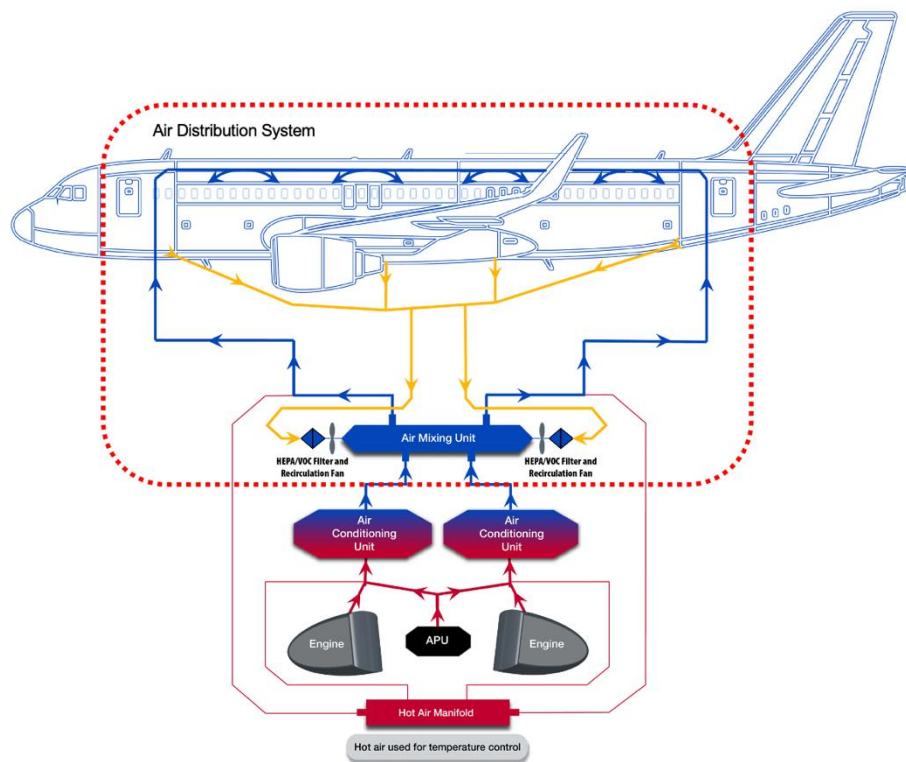


Figure 1-4 ECS schematic with Air Distribution System highlighted in red dotted box [19]

1.3 Aim and Objectives

Aim

To conduct a comprehensive experimental investigation of a Boeing 737-400 ECS. The results will be used to calibrate, and adjust accordingly, the IVHM Centre's in-house model-based simulation platform, SESAC, and investigate the role of humidity in ECS.

Objectives

- i. Perform a Literature Review on model-based diagnostics and full-scale simulation study on the ECS including experimental investigation.
- ii. Build a GTF to support research on civil aircraft diagnostics and prognostics.

- iii. Conduct shakedown test of the GTF and acquire experimental data for the Boeing 737-400 ECS PACK to support comparison between experimental and simulation data.
- iv. Develop a clear understanding of the control system governing the functionality of the system and implement within SESAC.

1.4 Methodology

To address the aim and objectives of this PhD, a methodological approach is constructed, which consists of 4 phases: Literature review, Experimentation, Simulation V&V and Thesis. The C1-C4 highlighted in Figure 1-5, are contributions planned to be achieved during the PhD.

Contribution 1: Literature review on diagnostic methodologies that can be applicable to the ECS.

Contribution 2: World's first-ever GTF on a Boeing 737-400 to be constructed. A comprehensive set of experimental data will be collected from the ECS.

Contribution 3: Experimental data analysis and comparison against SESAC.

Contribution 4: A study on the control system governing the PACK will be conducted. PACK Valve (PV) and TCV malfunction simulation study will also be conducted.

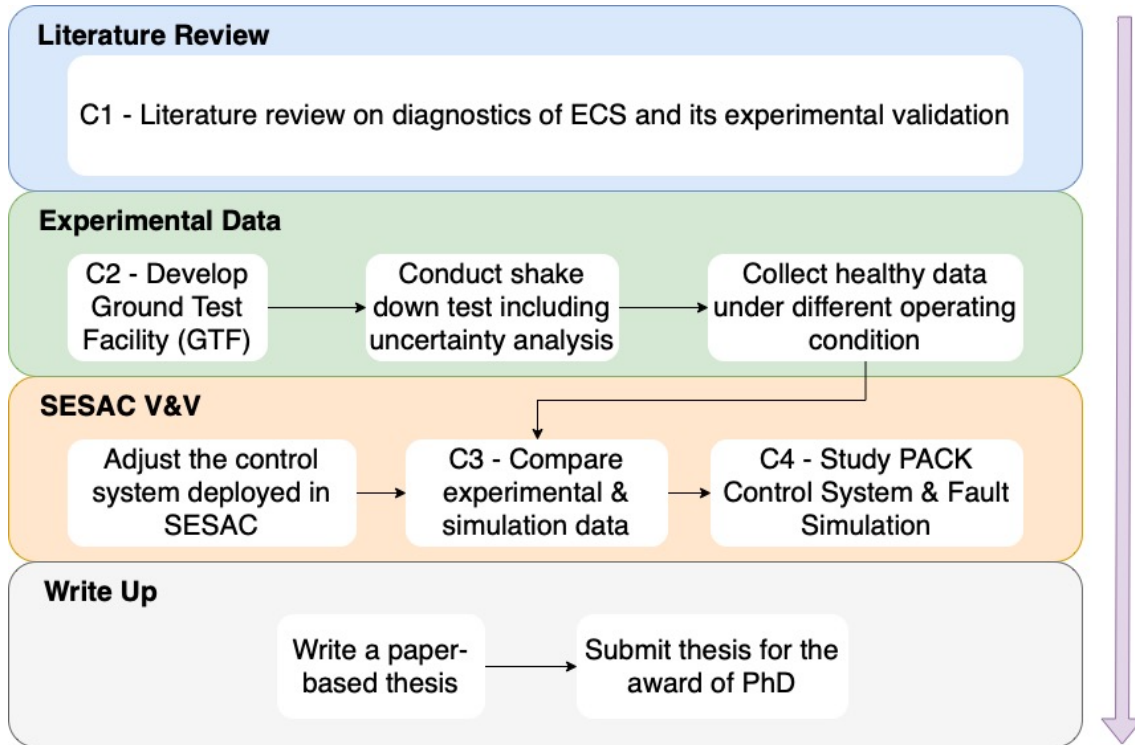


Figure 1-5 PhD Methodology

1.5 Layout of the Thesis

The PhD journey is captured in this paper-based thesis which consists of six chapters. This thesis is a compilation of papers that are written to publish the contribution made during this PhD study, except Chapter 1 (introduction) and Chapter 6 (Summary and Future Works). Chapter 2, 3, 4 and 5 are research articles consisting of specific introduction, literature review, methodology, results, and discussion related to respective research contributions. Therefore, key research findings from the literature review (chapter 2) are repeated in the introduction and literature review sections of subsequent chapters. A few minor changes were made to the papers to incorporate as chapters within the thesis.

Table 1-1 presents the list of chapters and their link to each contribution highlighted in Section 1.4. The following sections provide summaries of the chapters listed in

Table 1-1.

Table 1-1 List of thesis chapters

Chapter	Topic	Contribution	Publication status
2	Literature review	C1	Submitted to the Journal of Thermal Science and Engineering Applications
3	Research aim objective, methodology and overview	C1	Published in an Annual conference of Prognostic and Health Management 2019 [20]
4	Ground Test Facility	C2 and C3	Submitted to the Journal of Thermal Science and Engineering Applications
5	Control System	C4	Published in Journal of Thermal Science and Engineering Applications [21]
6	Summary and Future Work	-	-

1.5.1 Chapter 2: Recent Advances in the Diagnostics of the Aircraft Environmental Control System

In this chapter a literature review on diagnostic methodologies applicable to the aircraft ECS PACK system is presented. It also investigates the existing system-level simulation models and experimental activities previously conducted on the ECS system. The outcome of this chapter includes:

Finding 1: A list of existing diagnostic methodologies that can be used on the aircraft ECS system.

Finding 2: The open literature lacks a comprehensive investigation on the civil aircraft WS within the PACK.

Finding 3: A comprehensive list of full-scale ECS simulation platform developed are identified. It has been noted that most of these models have been developed primarily for design and analysis purposes, except for SESAC which has been purposefully developed for diagnostics with the capability to perform fault simulation investigation.

Finding 4: A need for a 737 GTF for experimental investigation on civil aircraft PACK performance at ground operation and to support V&V of SESAC.

Finding 5: There is a lack of emphasis on the study and impact of control system on PACK performance.

1.5.2 Chapter 3: A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics

The methodology presented in Section 1.4 is the revised version of the one presented in Chapter 3. Based on the gaps identified in Chapter 2, a methodological approach and experimental plan for full-scale experimental investigation on the ECS PACK performance is proposed. The GTF will be used for in-situ PACK performance analysis and V&V of SESAC. This chapter also contains some simulation results which are a baseline for understanding the aircraft data. Note that, due to time restraint, the diagnostic and humidity study is omitted from the thesis and proposed as the future work at the end of this thesis.

1.5.3 Chapter 4: A Novel Boeing 737 Ground Test Facility for the Experimental Investigation of a Civil Aircraft ECS

In this chapter the development of the 737 GTF is systematically reported. A discussion on the employed sensors and the uncertainty associated to the measurement is outlined based on laboratory tests. The aircraft data collected under different operating conditions, i.e, trim on-off and hot-cold demand is presented and the effect of trim system on the overall PACK performance is discussed. The overall investigation suggests a reasonably good match between experimental (aircraft) and simulation data (SESAC), the maximum average relative difference between the data and simulation in terms of Temperature, Pressure and Mass flow is found to be 2%, 8% and 6%, respectively. From this

study it has been identified that the control system plays a significant role in impacting the PACK performance, for which an end-to-end ECS instrumentation (BAS to cabin) and experimental analysis is deemed to be necessary for supporting accurate simulation and diagnostics of the ECS.

1.5.4 Chapter 5: Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate Fault Simulation

Chapter 4 suggested the control system to be a key player in dictating the overall PACK performance and that there is very limited research on the PACK control system. In light of that, this chapter provides a comprehensive explanation of the PACK control system elements (principally valves) and verifies their operation based on experimental test data acquired from the 737 GTF. This chapter also presents the fault capturing capability of the GTF, by presenting data that has been used to identify Ram door malfunction.

A discussion of the control system used in the simulation is then given, resulting in the correct temperature, pressure and flow being delivered to the cabin. The overall simulation results are then presented to demonstrate the importance of employing a systematically derived control logic. They are then further used to assess the impact of degradation in the main PACK valves [21].

1.5.5 Chapter 6: Summary and Future Works

In this chapter, a summary of the PhD is provided highlighting the contributions that have been made. Based on the remaining gaps that are yet to be addressed and the capability of the 737 GTF, future work is recommended in this final chapter of the thesis.

1.6 List of Publications

Published:

Journal:

- i. Chowdhury, S. H., Ali, F., and Jennions, I. K. (March 8, 2022). "Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate

Fault Simulation." ASME. *J. Thermal Sci. Eng. Appl.* September 2022; 14(9): 091008. <https://doi.org/10.1115/1.4053740>

Conference:

- i. Chowdhury, S. H., Ali, F., & Jennions, I. K. (2019). A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics. *Annual Conference of the PHM Society*, 11(1). <https://doi.org/10.36001/phmconf.2019.v11i1.888>

Submitted:

- i. Chowdhury, S. H., Ali, F., and Jennions, I. K. (2022). " A Novel Boeing 737 Ground Test Facility for the Experimental Investigation of a Civil Aircraft ECS."
– In review for publication in the ASME. *J. Thermal Sci. Eng. Appl.*
- ii. Chowdhury, S. H., Ali, F., and Jennions, I. K. (2022). "Recent Advances in the Diagnostics of the Aircraft Environmental Control System"
– In review for publication in the ASME. *J. Thermal Sci. Eng. Appl.*

References

1. Airandspace. Inventing A Flying Machine. Smithsonian National Air and Space Museum. Available at: <https://airandspace.si.edu/exhibitions/wright-brothers/online/fly/1903/>
2. CAA. How Safe is Aviation. Available at: <https://www.caa.co.uk/Safety-initiatives-and-resources/Aviation-safety-review/How-safe-is-aviation/> (Accessed: 3 April 2022)
3. Zhang G., Wang J., Lv Z., Yang Y., Su H., Yao Q., et al. A integrated vehicle health management framework for aircraft. 2015 IEEE Conference on Prognostics and Health Management (PHM). 2015; : 1–8. Available at: DOI:10.1109/ICPHM.2015.7245034
4. Jennions IK. Integrated Vehicle Health Management Perspectives on an Emerging Field. Jennions IK (ed.) Integrated vehicle health management Perspectives on an Emerging Field. Warrendale, PA: SAE International;

2011. Available at: DOI:10.4271/R-405
5. Figuero DV. Diagnostic Capability for Environmental Control Systems. Universidad Politécnica de Madrid, Cranfield Univeristy; 2017.
 6. Skybrary. B738, Glasgow UK, 2012. 2012. Available at: https://www.skybrary.aero/index.php/B738,_Glasgow_UK,_2012 (Accessed: 26 June 2019)
 7. AeroInside. Yan Boeing 737-400 near Kiev on Jun 23rd 2018, loss of cabin pressure. 2018. Available at: <https://www.aeroinside.com/item/11657/yan-b734-near-kiev-on-jun-23rd-2018-loss-of-cabin-pressure> (Accessed: 1 March 2020)
 8. Skybrary. B735, en-route, SE of Kushimoto Wakayama Japan, 2006. 2006. Available at: https://www.skybrary.aero/index.php/B735,_en-route,_SE_of_Kushimoto_Wakayama_Japan,_2006 (Accessed: 26 June 2019)
 9. Skybrary. B737 en-route, Glen Innes NSW Australia, 2007. 2017. Available at: https://www.skybrary.aero/index.php/B737_en-route,_Glen_Innes_NSW_Australia,_2007 (Accessed: 26 June 2019)
 10. Scott M. Development of a Realistic, Automated, & Efficient Reliability Development Growth Test for a Large, Distributed, Environmental Control System. SAE Technical Paper Series. 1999. Available at: DOI:10.4271/1999-01-2165
 11. Majeed O. Aircraft Environmental Control Systems. Carleton University AERO 4003 Lecture. 2010.
 12. Jennions I., Ali F., Miguez ME., Escobar IC. Simulation of an aircraft environmental control system. Applied Thermal Engineering. May 2020; 172: 114925. Available at: DOI:10.1016/j.applthermaleng.2020.114925
 13. Skybrary. Aircraft Bleed Air Systems. Available at: <https://skybrary.aero/articles/aircraft-bleed-air-systems> (Accessed: 3 April

2022)

14. Baptista M., Henriques EMP., de Medeiros IPP., Malere JPP., Nascimento CLL., Prendinger H. Remaining useful life estimation in aeronautics: Combining data-driven and Kalman filtering. *Reliability Engineering and System Safety*. Elsevier Ltd; 2019; 184(April): 228–239. Available at: DOI:10.1016/j.ress.2018.01.017
15. Vega Diaz R. Analysis of an Electric Environmental Control System to Reduce the Energy Consumption of Fixed-Wing and Rotary-Wing Aircraft. Cranfield University; 2011. Available at: https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/7422/Rolando_Vega_Diaz_Thesis_2011.pdf?sequence=1&isAllowed=y
16. Devadurgam H., Rajagopal S., Munjulury RC. Analytical Design and Estimation of Conventional and Electrical Aircraft Environmental Control System. : 1–14. Available at: DOI:10.31224/osf.io/gu4pz
17. Genty A., Saunders A., Cimino JP., Rose S. Environmental Control System for Light Turbo Prop. 33rd International Conference On Environmental Systems. SAE International; 2003. pp. 1–9. Available at: DOI:10.4271/2003-01-2400
18. Shang Y., Wang J., Bi Y., Jian Y., Pei Y., Yuan W., et al. Air dehumidification by membrane with cold water for manned spacecraft environmental control. *MATEC Web of Conferences*. 2017; 114: 1–7. Available at: DOI:10.1051/mateconf/201711402011
19. Pall. How Cabin Air Filters Work. 2022. Available at: <https://www.pall.com/en/aerospace/commercial-fixed-wing/how-cabin-air-systems-work.html> (Accessed: 3 April 2022)
20. Chowdhury S., Ali F., Jennions I. A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics. *Proceedings of the Annual Conference of the PHM Society* 2019. 2019. pp. 1–11. Available at:

DOI:<https://doi.org/10.36001/phmconf.2019.v11i1.888>

21. Chowdhury S., Fakhre A., Jennions IK. Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate Fault Simulation. Journal of Thermal Science and Engineering Applications. 2 February 2022; : 1–18. Available at: DOI:10.1115/1.4053740

2 Recent Advances in the Diagnostics of the Aircraft Environmental Control System

‘Education is not the learning of facts, but the training of the mind to think.’

- Albert Einstein

This chapter discusses the diagnostic approaches applicable to fault detection and isolation of the aircraft air conditioning unit, as well as its predictive maintenance (PM). The PM approach allows a reduction in downtime, lowering the Maintenance, Repair and Overhaul (MRO) costs through condition monitoring and diagnostics. In this chapter, the diagnostic methodologies applicable to the aircraft Environmental Control System (ECS) are studied to construct a taxonomy of diagnostic techniques. A review of the literature suggests model-based and data-driven methods are effective on fault detection and isolation (FDI) for air-conditioning systems. However, findings from this chapter indicate that the model-based diagnostic approach is extensively used on the ECS as it is not dependent on large quantities of data. The model-based approach predominantly relies on the accuracy of the model for which the models to be used for diagnostic purposes requires experimental verification and validation. Although a substantial amount of work has been conducted on developing simulation models and diagnostic strategies for the ECS, this literature review suggests that there is a compelling need for a verified and validated ECS model to allow system-level diagnostics. It has also been identified that a comprehensive study on the humidity regulation and the effect of control system on the PACK performance is missing from the open literature.

Table 2-1, shows the table of content for this chapter. This chapter is currently in process of submission to a journal for publication.

Table 2-1 Overview of Chapter 2

2.1	Introduction
2.2	Diagnostic Methodologies
2.3	System-Level Simulation of ECS
2.4	Experimental Work on the ECS Diagnostics
2.5	Conclusions

2.1 Introduction

2.1.1 Background

The ECS of an aircraft provides conditioned air to pressurise the cabin and regulate the temperature and humidity. It also supplies the cooling air into the avionics bay to prevent the electronic equipment from overheating. It contains two Passenger Air Conditioners (PACK), which are the primary system for conditioning the airflow within the ECS. It is well designed, with minor, and occasionally major, faults not instantaneously affecting the output of the system [1]. Although the system is quite robust, there have been a few incidents reported due to system failure.

A simple ECS component fault occurrence can escalate and result in system failure. For example, a Ram air actuator failure can result in reduction of cold mass flow over the heat exchanger causing an instant PACK shutdown due to overheating [2]. Overheating can also occur due to a change of the bleed air source at the PACK input [3]. These incidents of PACK failure affect the pressurisation of the cabin. The PACK functionality is also crucial for maintaining humidity level in the cabin as overheating of excess moisture can cause misting in the cockpit, and the cabin, which can hinder the safety of passengers and crew [4].

The safety of the crew and operational cost was a major concern when NASA began human space flight [5]. After the Apollo success the concept of Integrated Vehicle Health Management (IVHM) began to surface in the 70s to

address the safety and cost factors. In 1992, NASA defined the IVHM goals and objectives in a report [6]. These objectives can be summarised as the capability to facilitate optimised maintenance actions, operational cost reduction, improved readiness of the fleet and enhanced safety [7].

Zhang et al. [8] suggested that 31 billion USD in a year is spent by airlines for maintenance of their fleet. This motivates airlines to take the IVHM concept developed by NASA further by integrating health monitoring technologies into their asset [9]. It helps in monitoring the critical components of a system of their asset and cuts down on unscheduled maintenance and downtime [10]. Thus, the use of IVHM toolsets is enabling a shift from preventive maintenance over to the predictive maintenance.

The data collected from the aircraft is instrumental in conducting diagnostics and prognostics using the model-based or data-driven technique. Then a vehicle level reasoning system can be used to identify faults considering the interaction between different systems [11]. In order to understand interdependencies between components, and to enable accurate diagnostics there is a need to develop system-level simulation models. The fault detection and prediction analysis can dictate the supply-chain and logistics to best prepare for scheduled maintenance, creating the new manufacturing paradigm supporting predictive maintenance [12, p.4].

2.1.2 Environmental Control System

Air conditioning systems are designed to provide conditioned air ensuring human comfort. They are applicable in aircraft, automobile, offices, industries and various other places. During the mid-1940s, the pioneering Boeing 307 Stratoliner was the first aircraft equipped with air conditioning system, ECS, for cabin pressurisation. This enabled high altitude flights within thin air and sub-zero temperature regions above the weather and turbulence [13,14].

Figure 2-1 shows a typical ECS architecture. The ECS uses multiple subsystems (i.e. BAS, PACK and ADS) including a control system regulating flow across the system to meet temperature and pressure requirements in cockpit, cabin and avionics bay. The bleed system provides the pressurised air to the

PACK for conditioning. Part of the bleed mass flow before entering the PACK is taken out to drive the Ram turbofan to drive cold ambient air over the heat exchangers in the PACK to enable pre-cooling of the bleed air. After conditioning of the bleed air in the PACK, the air is mixed with trim and recirculating air from the cabin in the mixing manifold before it is distributed to different zones of the aircraft.

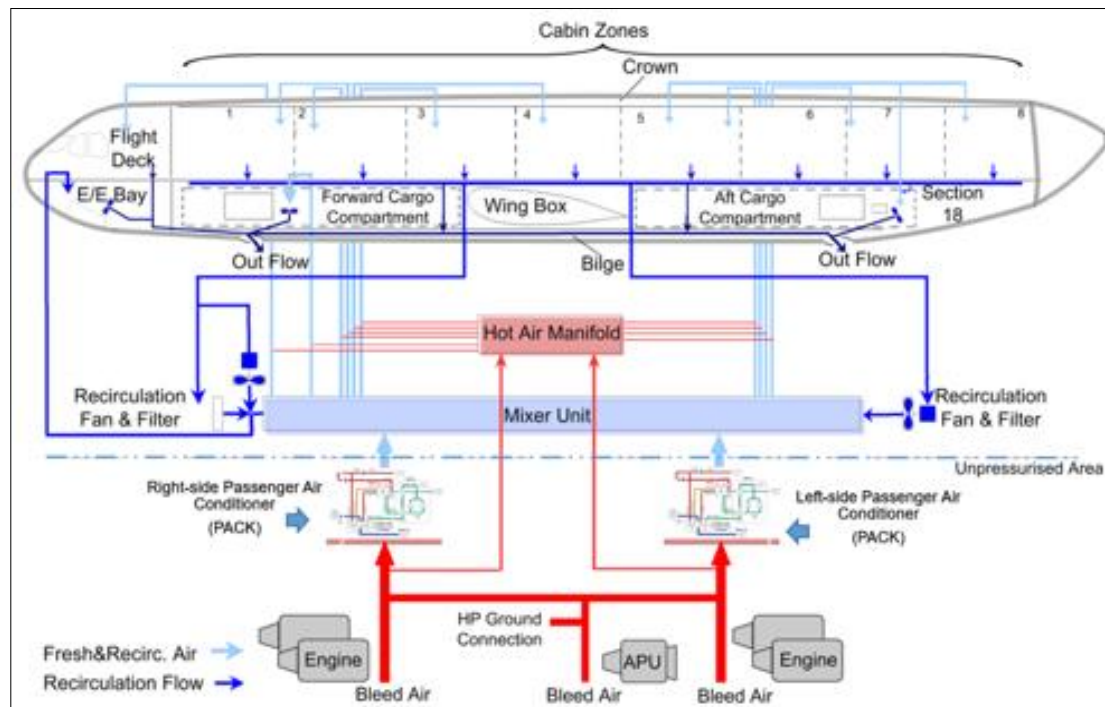


Figure 2-1 ECS schematic [15]

The PACK is the primary system for conditioning the airflow within the ECS. Figure 2-2 illustrates the schematic of a single PACK with HPWS in a B737-400 aircraft. It consists of Valves, Heat Exchangers, an Air-Cycle Machine (ACM) and a High-Pressure Water Separator (HPWS). There are other ECS systems, such as electrically driven ECS (used in modern aircraft) [16, p.3], pneumatic ECS with low-pressure water separator (LPWS) (generally used in older generation aircraft) [17], vapour cycle ECS (used for light turboprop aircraft application) [18] and membrane-based dehumidifier (used in spacecraft) [19].

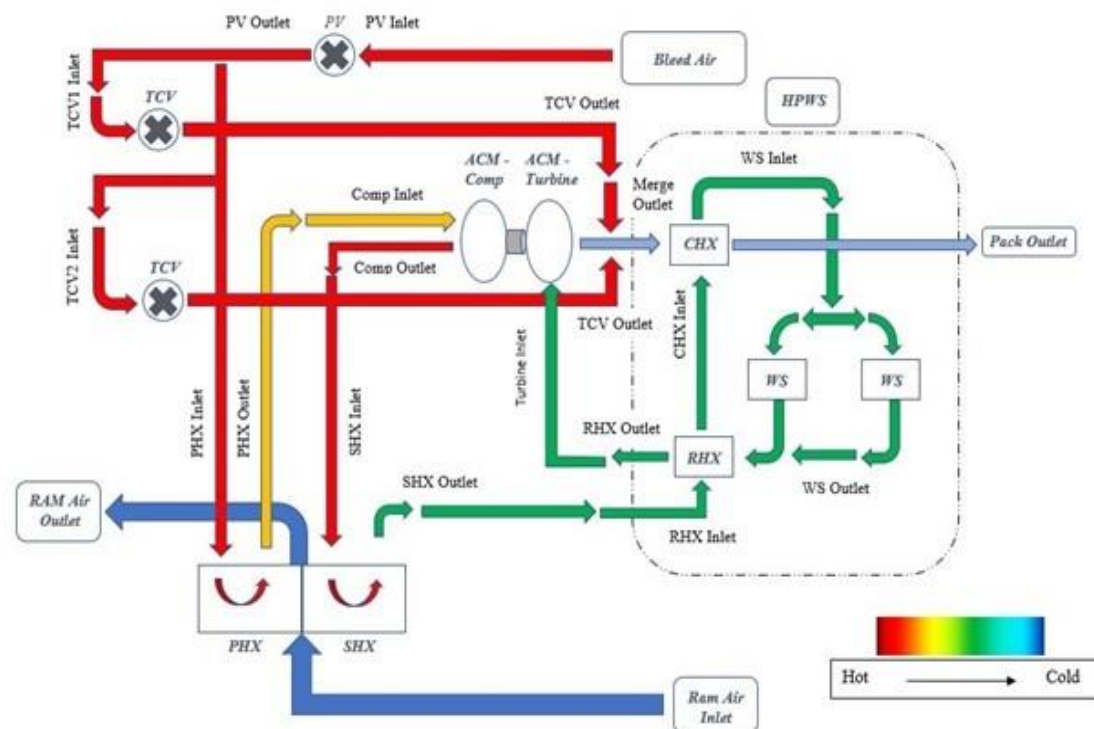


Figure 2-2 Schematic of the 737-400 ECS PACK with HPWS

The PACK consists of a PACK valve (PV) and Temperature Control Valves (TCV) which regulate the hot mass flow through the system and the core. The Primary Heat Exchanger (PHX) and Secondary Heat Exchanger (SHX) use the cold Ram air as a heat sink. In between the heat exchangers sits the refrigeration unit of the PACK. The ACM drives the air through the core and contributes to cabin pressurisation. Towards the end of the PACK sits the HPWS consisting of Reheater (RHX), Condenser (CHX) and Water Separator (WS) which regulates air temperature to enable condensation and extraction of water from the air to regulate humidity. The PACK has a control system that governs the opening of the valve by using temperature sensors at the WS outlet (to regulate the TCV opening) and Compressor outlet (to regulate the Ram air mass flow modulating door) to meet cabin demand temperature. In addition to that, there are three temperature switches: at the compressor outlet, WS outlet and PACK outlet, which shut down the PV to prevent any damage to the system in the case of overheating.

2.1.3 Integrated Vehicle Health Management

After the introduction of IVHM by NASA, the aviation industry started utilising it in accordance with the new Product Service System (PSS) business model. It helps in monitoring the critical components of a system of an asset and cuts down on unscheduled maintenance and downtime, defining the company's profit margin [10]. Unscheduled maintenance plays a key role in increasing operating costs. Deploying IVHM tools on expensive assets such as the aircraft, raises the profit margin through the reduction in downtime during maintenance and as a result enhancing fleet availability.

Figure 2-3 distinguishes between preventive and predictive maintenance. The manufacturing sector of the aviation industry typically follows the preventive maintenance approach where the aircraft is grounded frequently for routine maintenance regardless of fault occurrences. This increases downtime as all critical components go through thorough inspection. The idea of IVHM is to monitor the health condition of the critical systems using sensor technology to detect and predict fault occurrences. At the fault prognostics stage shown in Figure 2-3, the remaining useful life of components is estimated, based on that maintenance actions are planned. The early detection of failure and prognostics helps cut down on unscheduled maintenance and also ensures the safety of passengers and crew.

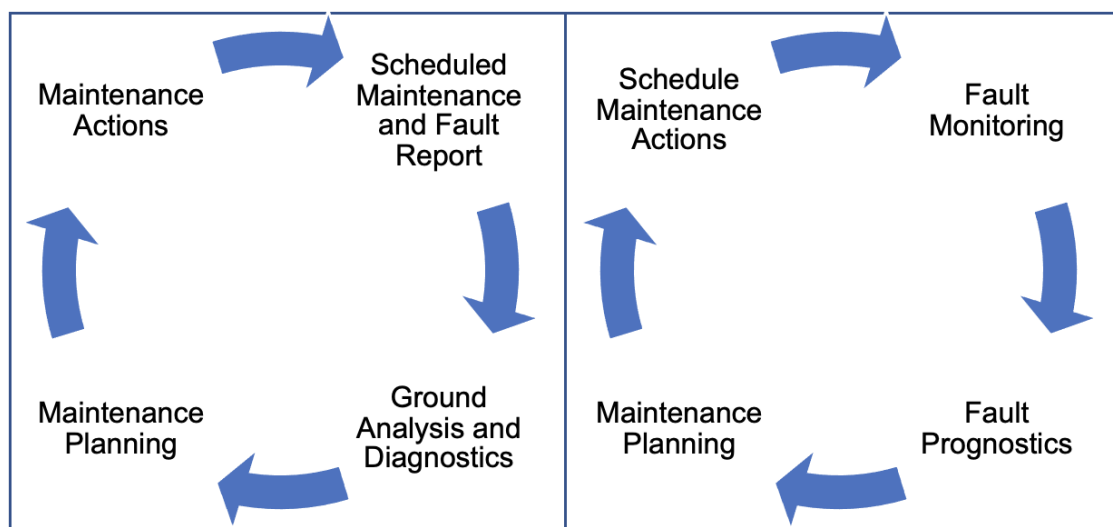


Figure 2-3 Maintenance flow chart: Preventive (left) & Predictive (right)

The sensor data collected from the aircraft is instrumental in conducting diagnostics and prognostics using a model-based or data-driven technique. In order to understand interdependencies between components to enable accurate diagnostics it requires development of system-level simulation model. Then a vehicle level reasoning system is used to identify faults considering the interaction between different systems [11]. This use of vehicle level reasoning proposed by Cordelia et al. [11], is a novel way of using reasoning to enable condition-based maintenance. The overall analysis of aircraft health condition and interdependencies between major systems can then be used to well prepare the maintenance actions [12, p.4].

2.1.4 Scope of Present Work

This chapter provides a literature survey on the ECS towards its diagnosis which includes:

- I. Identification of diagnostic methodologies applicable for the ECS
- II. A review on system-level simulation models for the ECS
- III. Experimental investigation on PACK performance

2.2 Diagnostic Methodologies

Heat exchangers within the PACK has been extensively investigated by researchers [20–23]. The aircraft ECS heat exchangers are made of fin and plate assemblies as shown in Figure 2-4, which uses cold Ram air as a heat sink to cool the hot bleed air. The Ram air often contains debris which accumulates at the cold-side of the heat exchanger resulting in a drop in heat exchanger effectiveness [24]. Due to drop in effectiveness the heat transfer across the hot and cold side will be impacted and the system will overheat imposing a risk of immediate PACK shutdown. Therefore, the heat exchangers were considered to be critical components of the aircraft ECS system which requires appropriate diagnostic rules [25]. The diagnostic methodology that has been implemented can be classified as: i) Model-based method [26], (ii) Data-Driven method [9] and (iii) Hybrid method [27]. The hybrid method is a combination of both model-based and data-driven methods.

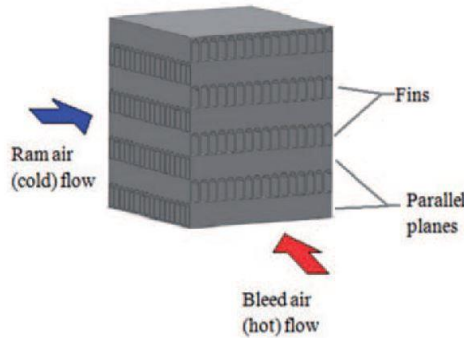


Figure 2-4 Typical fin-and-plate type cross-flow heat exchanger [25]

2.2.1 Model-based Method

The model-based method relies on a system model with the mathematical equations defining the input/output conditions [28]. This technique involves installing sensors at the optimised locations to acquire health defining parameters and comparing them against the model output. This sensor set is unique for each system and can be established by studying the thermodynamic PACK performance characteristics. This study of PACK performance characteristic under heat exchanger fouling is demonstrated by Jennions and Ali [29]. The heat exchanger fouling has been simulated in the model by manipulating the heat exchanger effectiveness. Their results suggests that the PACK performance under PHX and SHX degradation are very different to each other. The deviation between the model data (healthy baseline under given operating conditions) and test data can then be used as an indication of fault occurrences [30, p.19]. Figure 2-5 demonstrates a typical model-based approach that relies on residual evaluation. The difference, or residual, is usually generated by one of three different methods: (i) Parameter Estimation, (ii) State-observer and (iii) Parity Space [31].

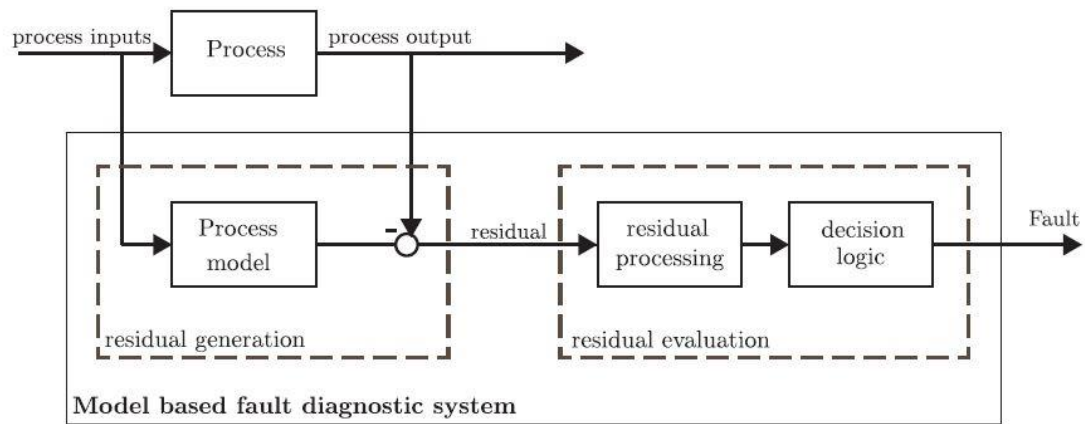


Figure 2-5 Concept of model-based diagnostic approach [30, p.19]

2.2.1.1 Parameter Estimation and State-Observer

Fouling in heat exchanger is due to particulate accumulation. This can occur in both the hot and cold side. Research indicates the parameters that needs to be monitored for diagnosing heat exchanger fouling are the heat transfer coefficient, the pressure drop, the mass flow rates, the temperature variation and the weight of the plates [32]. Deviation in the estimated parameters over time is used as an indication of fault occurrences. To estimate the values of model parameters using parameter estimation method a dynamic model of the system is required. An example of such dynamic model in the form of physical state space model representation of a heat exchanger is illustrated in Eq. 2-1 [32], where the hot inlet temperature ($T_{h,1}$), hot outlet temperature ($T_{h,2}$), cold inlet temperature ($T_{c,1}$) and cold outlet temperature ($T_{c,2}$) are the model state. The model parameters are α , β , τ_h and τ_c . A detailed discussion of the derivation and parameterisation can be found in the reference article [20]. Shah et al. [33] and Jonsson et al. [32] used extended kalman filter (EKF) on such state space model of heat exchanger to estimate the required parameters. The EKF is most commonly used to diagnose heat exchanger fouling using the model-based technique [32–35].

$$\begin{aligned}
\frac{d}{dt} \begin{bmatrix} T_{h,1} \\ T_{h,2} \\ T_{c,1} \\ T_{c,2} \end{bmatrix} &= \begin{bmatrix} -(1 + \frac{\alpha}{2})/\tau_h & 0 & \frac{\alpha}{2\tau_h} & \frac{\alpha}{2\tau_h} \\ (1 - \frac{\alpha}{2})/\tau_h & -(1 + \frac{\alpha}{2})/\tau_h & \frac{\alpha}{2\tau_h} & 0 \\ \frac{\beta}{2\tau_c} & \frac{\beta}{2\tau_c} & -(1 + \frac{\beta}{2})/\tau_c & 0 \\ \frac{\beta}{2\tau_c} & 0 & (1 - \frac{\beta}{2})/\tau_c & -(1 + \frac{\beta}{2})/\tau_c \end{bmatrix} \\
&\times \begin{bmatrix} T_{h,1} \\ T_{h,2} \\ T_{c,1} \\ T_{c,2} \end{bmatrix} + \begin{bmatrix} (1 - \frac{\alpha}{2})/\tau_h & 0 \\ 0 & \frac{\alpha}{2\tau_h} \\ 0 & (1 - \frac{\beta}{2})/\tau_c \\ \frac{\beta}{2\tau_c} & 0 \end{bmatrix} \begin{bmatrix} T_{h,in} \\ T_{c,in} \end{bmatrix}
\end{aligned} \tag{2-1}$$

The traditional EKF used to estimate the state parameters for detecting degradation or fouling can potentially lose its monitoring capability in case of abrupt changes in the process states. This problem was resolved using two Kalman filters, simultaneously forming a double model filter [23] which is used to trace fault-free and faulty state of a non-linear system. For both the methods, the selection of the initialisation value for the parameter can be difficult, for which an adaptive filter such as strong tracking filter (STF) is developed by Ma et al. [34], to improve the existing EKF that can be used to estimate the fault parameters. The STF is an extension of the EKF which has the capability to perform online state estimation regardless of the system reaching steady-state [36]. The authors also used a modified bayes classification algorithm to detect and isolate fault [34].

Similarly, the state-observer method uses model input data to estimate state variables, based on suitable estimation method. Once the system output is reconstructed using the estimated state variables, error between the simulation and actual output is to be calculated which will be zero if the system is fault free, and vice versa [30]. For these two methods to be effective, it is essential to understand the input-output behaviour of the system [37]. For this, experimental component performance analysis is required.

The heat exchanger fouling can also be detected by analysing the PACK control system. The PV and TCV regulate mass flow through the system to match cabin demand temperature. The variation in hot and cold mass flow affects the heat transfer coefficient. The valves are regulated by a control signal which drives

the motor to rotate a butterfly valve. Given the Ram mass flow is constant, estimating the deviation of valve command from fault free condition can also help identify heat exchanger fault occurrence. Shang and Liu [25] proposed that the fault detection of the heat exchanger can be monitored by estimating the deviation of valve control command using Kalman filter. The proposed methodology as shown in Figure 2-6 is based on the error (ε) between the output temperature (T_{load}) and simulated output temperature ($\hat{T}_{load}$) and control command ($\hat{u}_{bypass}$).

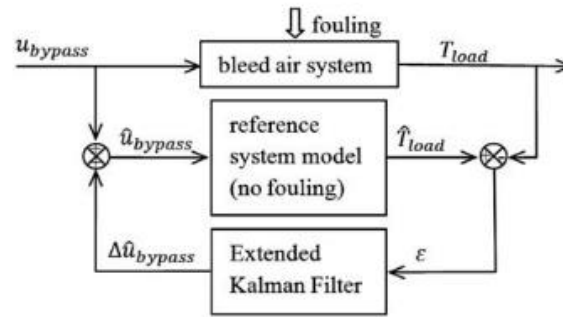


Figure 2-6 Heat exchanger fouling detection method based on TCV control command [25]

The valves regulating the mass flows in the PACK are regulated using series of temperature sensors installed at various locations across the ECS. These sensors can be faulty which can affect mass flow through the core of the PACK. Wang and Wang [38] developed a fault diagnosis strategy by employing a genetic algorithm technique for parameter estimation which can be used to detect sensor faults.

Another approach to heat exchanger fouling detection was proposed and experimentally validated by Palmer et al. [22], where a manually initiated built-in-test (iBIT) method was used. Within parameter estimation method Rajarman.S et al. [39], used Kharitonov's theory instead of the EKF, due to its suitability in handling multiplicative fault detection [31]. Furthermore, Matthew D. et al. [40,41], developed a physics-based approach in estimating RUL, where particle filter based on the parameter estimation method was implemented for predicting the life-cycle of a pneumatic valve with limited sensing conditions.

2.2.1.2 Parity-space

As opposed to the parameter estimation and state-space observer approach, the parity space approach works with the state-space representation of dynamic systems. Without requiring detailed knowledge in advanced control theory of the system, the parity-space diagnostic method works by developing a simple mathematical algorithm equating the input-output state vector and the past state vector [37, p.17]. Due to the use of simple algebraic equations with state-space equations the parity space is deemed to be simpler compared to observer approach in a study by Yu et al. [42].

Mostofi et al. [43] used this parity-space method to develop a diagnostic algorithm to isolate the actuator and sensor faults in an automobile engine. The throttle angle has been taken as an input and engine revolutions, manifold air-pressure and temperature as the state variables as outputs. To avoid the complexity of a nonlinear state-space model, the Jacobian Method was used for linearization, and a parity matrix was formed which was then used to design a weight matrix satisfying the residual matrix. The proposed diagnostic method has been validated using real engine data. Similarly, Varrier et al. [44], conducted fault detection within a linear parameter varying systems where parity space approach was used, including the time-varying parameters in the parity matrix.

The parity-space approach has the capability to detect additive faults and to check the sensor deviations effectively, however, it is sensitive to noise. Hwang and Huh [45], developed a diagnostic method coupling the parity-space and observer approaches to achieve effective diagnostic capability. Numerous other studies exist that used parity-space for detecting faults when noise has been injected into the system. These include using the parity-space approach for handling nonlinear systems and system behavioural indicative matrix for power trains [46–48].

2.2.2 Data-driven Method

The data-driven method for diagnostics can be fundamentally categorised into: (i) Statistical, and (ii) Artificial-Intelligence.

2.2.2.1 Statistical

The data-driven method is solely dependent on the quality and quantity of the data being collected from the model without having prior domain knowledge on the physics governing the functionality of the system. The output of systems such as the ECS is influenced by more than one parameter, which necessitates multivariate statistical analysis (MSA). The Principal Component Analysis (PCA) approach within the MSA framework is popular due to its efficiency in minimising mean squared distance between high dimensional and complex data points to analyse data variability (i.e. deviation between the healthy case and faulty data sets) [49,50].

The heat exchanger of the ECS is a complex system in which the output is dependent on both the inlet temperature on the hot-side and the mass-flow rate and temperature of the Ram air in the cold-side. Najjar et al. [51] adapted PCA technique for extracting features to analyse the output temperature of the heat exchanger. From the extracted principal components of the heat exchanger, faults were classified using Support Vector Machine (SVM) and k-Nearest Neighbor (k-NN) methods to recognise the pattern within the data set. Similarly, the PCA approach has been proven to enhance FDI capability through automatic identification of the diagnostic signals obtained [52,53].

2.2.2.2 Artificial-Intelligence

Expert system

An expert system is a rule-based decision-making technique which is often used in the realm of data-driven diagnostics. It first emerged in the 1970s and was one of the successful forms of AI techniques [54]. Bruton et al. [55] in their literature review suggested the expert system to be relatively easy to develop, however, the disadvantage is that it requires complex rules for complex systems. It is also suggested that rule-based expert systems FDI method have excellent potential for market deployment due to its relatively straightforward development process.

Fuzzy logic

Fuzzy logic, first introduced in 1965, works by defining partial truth values ranging between 0 and 1 [56]. These fuzzy sets help to represent imprecise information

in terms of numerical values. Once fuzzy variables are obtained, if-then rules can be developed for fault classification [57].

The fuzzy-model-based control scheme was developed to predict performance for the control system of a building air conditioning system with existing water-side and air-side fouling on a heat exchanger [58]. Fuzzy model and rule-based methodologies have limitations after a certain point of accuracy. As highlighted by Najafi et al. [59], as the complexity of the system develops, it requires substantial effort in adjusting and tuning fuzzy sets either manually or through complex algorithms. Subsequently, the complexity in the rule-based method increases with the rise in complexity of the system failure (to the point when there is a higher level of uncertainties and measurement errors). For those circumstances, the machine learning approach was taken where a behavioural pattern was to be generated from previous fault knowledge and comparing that with the observed behaviour of the system [59]. This method heavily depends on the amount of data available for developing a base-line behavioural pattern for the system.

Artificial Neural Network (ANN)

The ANN is a branch of the machine learning technique in diagnostics of system failure. The ANN method was developed by depicting biological neural networks with neurons and the connection between them. The ANN model consists of three layers - input, hidden, and output – of which the weights and biases need to be parameterised to fit the data set [60]. This method does not require domain knowledge of the system, but it requires data sets to train the algorithm [61]. It can be used to conduct behavioural analysis to develop patterns which are then used for FDI [62]. The ANN technique was applied in the ECS for system-level fault detection and isolation by developing diagnostic tree defining the entire system as the input node with the components as the branches [63]. The neural network model and algorithm was constructed to isolate faults in a top-down fashion.

Allen et al. [64] combined the fuzzy model and ANN pattern recognition techniques to perform fault detection and classification. This method was

suggested to be effective due to its capability of solving complicated nonlinear systems. To further improve the fault detection capability, a dual-neural network structure coupled with subtractive clustering analysis technique was developed [65]. Another approach to machine learning is to implement Deep Neural Network (DNN), which uses hidden layers between the input and output layers [66]. Data-driven techniques are now prevalent in the industry and academia; however, the model-based approach for fault detection has been popular in the past and still used by researchers [67–69].

2.2.3 Hybrid Method

A model can either be static or dynamic [70]. The dynamic models are deemed to be more robust, as it can reduce the difference between the model and the actual system output by taking into consideration the degradation of the component through time [28]. These types of models are mostly a set of differential equations. The static models are developed using polynomial equations, which depends on the physical process constraints (i.e. effectiveness, resistance and flow rate). These parameters can be partially known or unknown and need to be estimated and converged to eliminate noise from the residual outcome. Yang X. et al. [71], suggested further research on using a hybrid model combining both model-based and data-driven methods which are predicted to be able to isolate fault under noise conditions.

The variation of the physical process constraints such as the heat exchanger effectiveness, resistance and flow rate, giving a converged residual value from model data and actual system data can indicate the faulty component [70]. However, this method is difficult to implement on dynamic models in which the fault propagates with time.

Finding 1: The FDI capability can be fundamentally obtained through either model-based or data-driven or both techniques combined. It is noticed that for the aircraft ECS system, *the model-based approach is more popular than the data-driven approach*. This is due to the scarcity of data available from the aircraft. The classification of the FDI methods and their advantages/disadvantages which are deemed applicable to the aircraft ECS system is highlighted in Table 2-2.

Table 2-2 Classification of Diagnostic methodologies

FDI methods	Techniques		Advantages	Disadvantages
Model-based	Parameter estimation		• Ideal for multiplicative/dynamic fault (i.e. fault propagating through time) • Does not require historical data	• Requires accurate modelling of the system
	State-observer	Kalman filter	• Can deal with modelling/parametric uncertainties • Use of two filters has been proven to have the capability to withstand abrupt changes in the system	• Requires prior knowledge of the system • Sensitive to modelling errors
		Extended Kalman filter	• Can reduce approximation error	• Fault detection capability can be hindered due to abrupt degradation or fouling (i.e. change in state)
	Parity-space		• Effective on non-linear system • Detail knowledge on advanced control theory of the system is not required	• Sensitive to noise • Requires accurate modelling of the system
Data-driven	Artificial intelligence	Artificial neural network	• Can work on complicated non-linear system • Does not require system model	• Requires historical data to develop a pattern
		Fuzzy logic	• Easily understandable structure • Ideal for handling uncertainties in the system as it does not require precise inputs	• Requires substantial effort in tuning fuzzy sets after the system fault becomes complex • Dependant on assumption due to its rule-based decision-making functionality
		Expert systems	• Relatively easier development process	• Less effective on complex system as they have higher uncertainty
	Statistical	Principal component analysis	• Effective on complex system with multidimensional data set	• Dependent on the quality of data to be analysed

Finding 2: *The open literature lacks comprehensive study on the ACM and the HPWS. The ACM can impact the overall performance of the PACK functionality as demonstrated by Santos et al. [72] where the authors conducted a thermodynamic analysis on a 3 wheel bootstrap ACM. This study validates the need for investigating the ACM in greater depth. Furthermore, an in-depth study on the humidity regulation and the diagnostic of HPWS is missing in the open literature.*

2.3 System-Level Simulation of ECS

Complex systems such as the ECS requires system-level analysis, as there are components such as valves which can mask any fault occurrence and fault can also propagate through the system. There are only a few full-scale simulation models available for the ECS. They were mostly developed for assisting in designing a new component. These simulation models are cost-effective ways of testing a model before it goes into manufacturing and tests. As these simulation models provide a detailed understanding of the system, they can be used for diagnostic purposes. This section discusses the existing models of the ECS and their functionality.

2.3.1 FLECS: Functional Model Library of the Environmental Control System

FLECS is an ECS modelling library programmed using MATLAB/Simulink software packages [73]. It is a project conducted by Airbus, Hamburg University of Applied Science and CeBeNetwork GmbH to construct a system-level model for the ECS. The library contains healthy models of different component blocks from BAS, PACK, valves, mixing manifold and cabin. Each of the subcomponents were taken as an individual module and were designed based on one dimensional thermodynamic equations and control system [74].

A simulation model of the ECS system was built within FLECS consisting of ducts and cabin model. After performing a comparison study with other existing simulation data, the model was verified based on temperature data collected at the supply duct inlet, PACK outlet and cabin inlet, during a test flight of Airbus A340-600. The acquired temperature data from the cabin inlet demonstrated good match [74]. The verification did not include pressure and mass flow data.

2.3.2 Flowmaster

Flowmaster software is commonly used in the aerospace industry for modelling. It is a 1-D thermo-fluid systems simulation that linearises model coefficients to achieve good convergence properties. Tu, Y. and Lin, G. P. [75] developed an ECS model using FlowmasterV7, which is programmed in C++ language, and the sub-block parameter method was used for mathematical modelling of the

components. The work focused mostly on developing the cabin temperature control system using expert Proportional-Integral-Derivative (PID) controller, which uses the fuzzy algorithm to adjust the PID parameters [1]. The effect of the specific humidity of the flow to model the heat exchanger (wet and dry) and ACM was considered. Both steady-state and dynamic analysis was validated experimentally with a maximum and minimum deviation of 4.3°C and 0.2°C [75]. It is to be noted that the verification did not involve pressure and mass flow readings.

Although the simulation models were primarily for design and development purposes rather than fault detection and isolation, Flowmaster simulation software has been used for fault detection for another system. Lang X. et al. [76] researched to detect pipe leakage based on the feature extracted from the pressure signal. Wavelet analysis was conducted for noise removal, and Least Square Twin Support Vector Machine (LSTSVM) method was used for leakage detection.

2.3.3 Easy5

Back in 1976, The Boeing Company developed Easy4 which later became Easy5. This software was developed for the need of having one single simulation modelling platform that can be used to create both nonlinear and linearised analysis of dynamic systems. The library was developed based on the SystemMS a modular modelling system. Easy5 also supports additional components created using Fortran. It is only required for the user to organise the components to be placed according to the desired model and the interconnection between the components are formed by the built-in Model Generation Program [15]. This includes defining the physical driving quantities such as forces, flow rates, velocities and other variables depending on the input parameters defined by the user. It also includes an Analysis Program which permits dynamic, static, linear and nonlinear analysis of the model after all the required input parameters are set. This software can run frequency response analysis, steady-state analysis and optimal controller synthesis [77].

Easy5 was later used by Boeing for developing an aircraft ECS model for simulation analysis. Following that, Hoffman [15, 78] reported the use of Easy5 for simulation of F-14 fighter aircraft ECS. In another study Gulfstream Aerospace used this software for developing the ECS model for G500 and G550 passenger jets [15, 79]. SAAB Group collaborated with Linköping Institute of Technology to model ECS for their fighter jet JAS39 Gripen. Fault modes identified from the historical data focusing mostly on the valve jamming was used to develop a state-observer model-based diagnostic method [15, 80].

2.3.4 Dymola

SAAB Group later migrated to Dymola as the ECS required major modifications. S-ECS system was modelled using the Modelica modelling language, which is then simulated in the simulation platform Dymola [81]. As suggested by Steinkellner [82] in a study, the model requires experimental verification and validation.

2.3.5 MATLAB/Simulink

For more than a decade, simulation modelling was based on arithmetic operations, integrators and transfer functions [83, p.7]. After Easy5 simulation platform, Mathworks developed the simulation environment called Simulink around 1991, which was a major shift to the paradigm of using ordinary differential equation (ODE).

Romani R. and De Goes L. programmed a cabin temperature control model using ODEs. The model has been validated by cabin temperature recorded under three different conditions: aircraft cooling in flight, aircraft heating in flight and pull-down scenarios [84]. The verification did not include Pressure and Mass flow readings. Although their results matched well with the data, their study lacks the modelling of the dynamic behaviour of the valves that have the potential to mask fault symptoms [15]. Furthermore, humidity has not been considered for simulation modelling.

2.3.6 SESAC: Simscape ECS Simulation for All Conditions

Cranfield University IVHM Centre on a funded project by the Boeing Company developed a computationally efficient and robust simulation framework for the ECS called - Simscape ECS Simulation for All Condition (SESAC) [15]. The components were constructed with simple algebraic equations based on their thermodynamic properties. SESAC is a component library which enables drag-and-drop component list that can be used to construct ECS models. This model can be used for analysing PACK performance characteristics under different operating conditions (i.e. in flight and on ground). It also supports both dry and wet simulation analysis. In comparison to Boeing's previous simulation model Easy5, SESAC can be used for fault simulation analysis. This model has been validated against Easy5 data provided by Boeing [85].

This ECS simulation model can be used for diagnostic purposes using model-based method by comparing model data and test data. The fault simulation analysis will provide knowledge of PACK performance under faulty condition which will subsequently support identification of optimised sensor location for fault detection. Diego [86], has used the SESAC and Thermodynamic model to propose five sensor location shown in Table 2-3 for identifying eight fault modes, as shown in Table 2-4.

Table 2-3 Optimal sensor set [86]

Variable	Sensor Name
Temperature	Temperature at the Primary Heat Exchanger Outlet
Temperature	Temperature at the Secondary Heat Exchanger Outlet
Temperature	Temperature at the Turbine Outlet
Pressure	Pressure at the Temperature Control Valve Marge Outlet
Pressure	Pressure at the Turbine Inlet

Table 2-4 List of faults in the ECS PACK provided by the industrial partner [86]

Name	Failure Mode
PACK Valve	Incorrect Valve Position
Temperature Control Valve	Incorrect Valve Position
Primary Heat Exchanger	Fouling or Blockage
Secondary Heat Exchanger	Fouling or Blockage
Reheater	Fouling
Condenser	Blockage Cold Side
Water Separator	Malfunction
Air Cycle Machine	Compressor or Turbine Malfunction
Ram Air Inlet Deflector Door	Malfunction

Finding 3: The list of models identified above is summarised in Figure 2-7. With the exception of SESAC, the simulation models have been primarily used for design and analysis purposes. Also, in order to be used for diagnostic purposes the models require experimental verification and validation at a system level [87]. *It is noted that the verification and validation of the models have not been done comprehensively.*

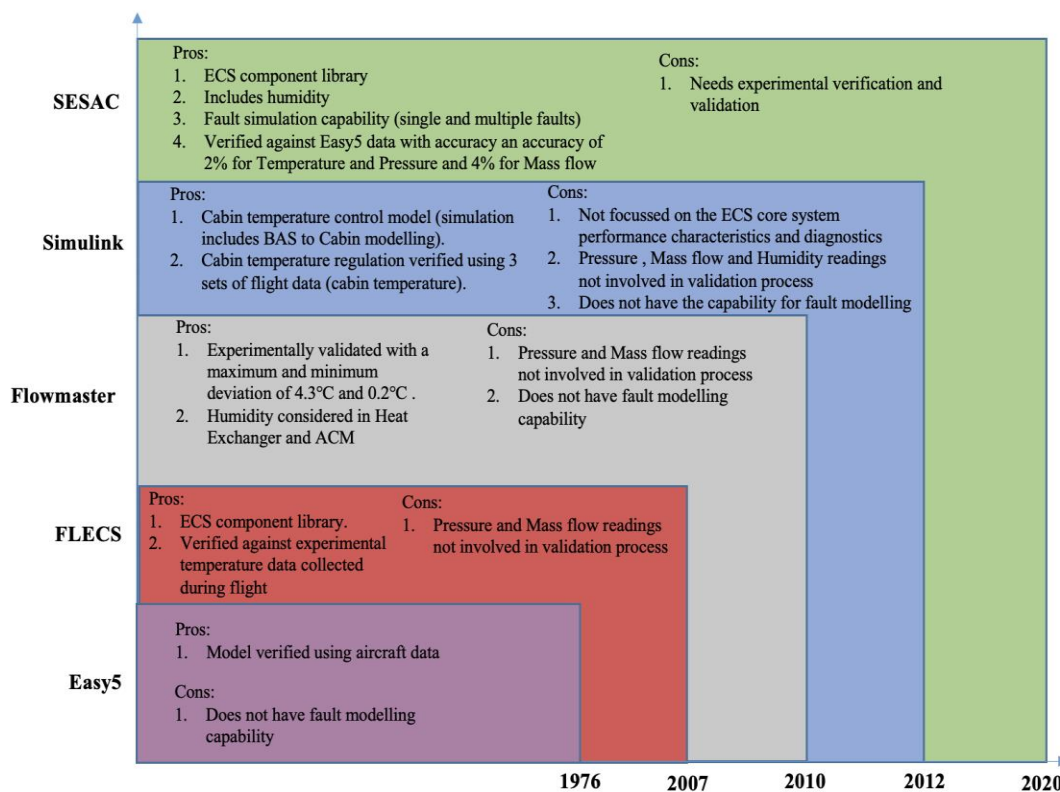


Figure 2-7 Existing ECS simulation models

Finding 4: The emphasis on the impact of control system failure (including valve malfunction) on PACK performance at a system level is missing in the open literature.

2.4 Experimental Work on the ECS Diagnostics

The simulation models used for developing diagnostic rules need to be experimentally verified and validated. In addition, the sensors used for condition monitoring also require appropriate calibration and validation. A faulty model and a misplaced sensor can produce a wrong diagnostic result, which can lead towards wrong maintenance action resulting in accidents and increased maintenance costs.

Honeywell-SECAN conducted an experimental investigation to validate the performance characteristics of a new LPWS design [88]. In contrast to the classical single stage water separator, a new two stage system with a coalescer

followed by water separating device was designed and tested. For experimental testing, a rig was developed with a compressor air inlet, water injection nozzle, turbine, diffuser and the coalescer under test. The rig set-up is shown in Figure 2-8. During the experimentation, the air flow rate was set, water injected to vary the humidity value and drop size distribution and pressure drop at coalescer outlet was measured. While this was to test the coalescer, for testing the separating device, an additional aspiration system was added to the rig to collect the separated water. The amount of water recovered at the WS outlet, in the turbine and in the air stream was measured. Data collected were used to calculate the overall efficiency of the WS for design validation [88].

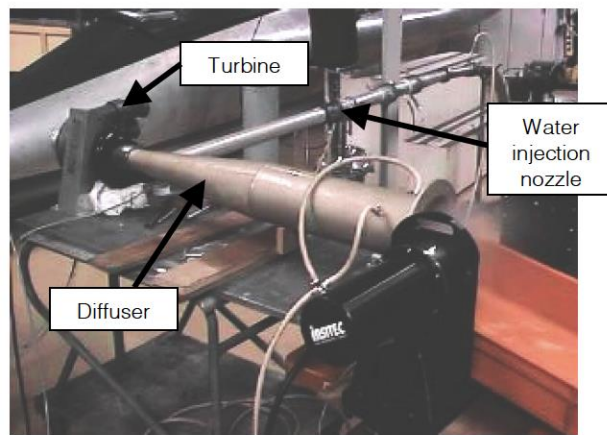


Figure 2-8 Rig set-up for LPWS Coalescer testing [88]

Childs et al. [89] developed a rig for testing BAE Systems fast-jet Hawk military aircraft ECS at Loughborough University. The two-wheel bootstrap cycle with LPWS ECS was set up in a lab environment. The rig was instrumented with temperature and pressure sensor, at the input and output of each component. The data collected from the rig was used to validate the 1D thermodynamic model by comparing the ECS coefficient of performance and system heat rejection. To test the diagnostic capabilities, Ram air inlet (to the SHX) was blocked, and the data collected was analysed. It was highlighted that a reduced Ram mass flow predominantly reduces the coefficient of performance of the ECS.

This rig was used to simulate faults and to conduct diagnoses at a system-level. The first failure mode analysis was on the blockage in the bleed air duct. It

was identified from the research that the blockage does not drastically affect its performance until cycle mass flow falls below 75% of its unblocked state. The TCV position testing showed that TCVs would comfortably mask any failure within the system [90]. Similarly, the rig was used to analyse the effect of humidity on system performance [90]. The results indicated that humid air impacts the ECS performance characteristics particularly at the ACM [91].

In collaboration with Boeing, Esperon-Miguez et al. [92] developed a thermodynamic model for the ECS capable of simulating faults in heat exchangers, valves and WS. The model has been validated using test data collected from a ground-based B737-200 aircraft which has a LPWS in the ECS. The ECS PACK was instrumented with thermocouples. The valve angles were measured using potentiometers. The rig set-up is shown in Figure 2-9. Two different types of experiments were conducted: healthy conditions and fault injected cases. Heat exchanger inlets were blocked using aluminium plates to reduce the effectiveness of the heat exchangers. Valves were regulated with potentiometer to fully open and fully closed scenarios. The coalescer bag was clogged without exceeding pressure differential. Using the healthy and fault injected temperature data collected the thermodynamic model was verified [92].



Figure 2-9 Experimental set-up on the B737-200 [92]

Finding 5 *There is a need to develop a civil aircraft in-situ ECS GTF targeting temperature, pressure, mass flow and humidity data collection.*

2.5 Conclusion

The necessity of having sophisticated health monitoring technology is rising as aircraft manufacturers are shifting towards a PSS type business strategy. The ECS failure resulting in sudden cabin depressurisation has caused many aircraft to make emergency landing. Furthermore, it has been reported that the ECS to be a major driver for maintenance. Thus, it is an area of interest for the manufacturers to investigate diagnostic approaches for detecting and isolating faults within the ECS system.

It has been identified that heat exchanger degradation has been extensively researched and model-based diagnostic technique has been widely used. There is very limited research available on the ACM and HPWS component degradation. This chapter has identified different diagnostic methodologies that are applicable to the ECS system. A taxonomy of the diagnostic methodologies, including its advantages and disadvantages, are demonstrated in Table 2-2.

In an integrated and complex system like the ECS fault propagates through the system and diagnosing fault requires knowledge on component interdependencies. To study the interdependencies between components within a system, a system- level simulation model is required. Furthermore, the control system governing the valves needs to be well designed as they can lead to misleading PACK performance simulation analysis. The emphasis on control system is missing in the open literature.

Finally, it was found that the models available for performing ECS simulation were used primarily for design and analysis purposes. These models have been verified with very limited data and have been mostly dependant on only temperature measurements. Therefore, it is deduced that there is a compelling need for a full-scale experimental facility to perform ECS analysis under different operating conditions and to use temperature, pressure and mass flow data to verify the models.

References

1. Tu Y., Lin GP. Dynamic Simulation of Aircraft Environmental Control

- System Based on Flowmaster. *Journal of Aircraft*. 2011; 48(6): 2031–2041. Available at: DOI:10.2514/1.C031433
2. Skybrary. B737 en-route, Glen Innes NSW Australia, 2007. 2017. Available at: https://www.skybrary.aero/index.php/B737_en-route,_Glen_Innes_NSW_Australia,_2007 (Accessed: 26 June 2019)
 3. Skybrary. B735, en-route, SE of Kushimoto Wakayama Japan, 2006. 2006. Available at: https://www.skybrary.aero/index.php/B735,_en-route,_SE_of_Kushimoto_Wakayama_Japan,_2006 (Accessed: 26 June 2019)
 4. Skybrary. B738, Glasgow UK, 2012. 2012. Available at: https://www.skybrary.aero/index.php/B738,_Glasgow_UK,_2012 (Accessed: 26 June 2019)
 5. Aaseng GB. Blueprint for an integrated vehicle health management system. 20th DASC. 20th Digital Avionics Systems Conference (Cat. No.01CH37219). IEEE; 2001. pp. 3C1/1-3C1/11. Available at: DOI:10.1109/DASC.2001.963350
 6. NASA. Research and technology goals and objectives for Integrated Vehicle Health Management (IVHM). Washington, D.C.; 2019. Report No.: NASA-CR-192656. Available at: <https://ntrs.nasa.gov/citations/19930013844>
 7. Science BA. Integrated Vehicle Health Management Technology and Its Applications in Commerical Aviation. 2017; Available at: DOI:10.1109/SDPC.2017.145
 8. Zhang G., Wang J., Lv Z., Yang Y., Su H., Yao Q., et al. A integrated vehicle health management framework for aircraft. 2015 IEEE Conference on Prognostics and Health Management (PHM). 2015; : 1–8. Available at: DOI:10.1109/ICPHM.2015.7245034
 9. Lightfoot H., Greenough RM. State-of-the-art in integrated vehicle health management. 2016; (March): 1–14. Available at: DOI:10.1243/09544100JAERO446

10. Grubic T., Jennions I., Baines T. The Interaction of PSS and PHM - a mutual benefit case. 2009. pp. 1–10.
11. Ezhilarasu CM., Skaf Z., Jennions IK. Progress in Aerospace Sciences The application of reasoning to aerospace Integrated Vehicle Health Management (IVHM): Challenges and opportunities. Progress in Aerospace Sciences. Elsevier Ltd; 2019; 105(December 2018): 60–73. Available at: DOI:10.1016/j.paerosci.2019.01.001
12. Mobley RK. An Introduction to Predictive Maintenance. Elsevier; 2002. 4 p. Available at: DOI:10.1016/B978-0-7506-7531-4.X5000-3
13. Pomata AE. Boeing 307 Stratoliner Pressurized Airliner. historylink.org. 2001. Available at: <https://www.historylink.org/File/3598> (Accessed: 14 September 2020)
14. Cooper JB. ALTITUDE CONDITIONING of Aircraft Cabins. SAE International. 1941. Available at: DOI:0148-7191
15. Jennions I., Ali F., Miguez ME., Escobar IC. Simulation of an aircraft environmental control system. Applied Thermal Engineering. May 2020; 172: 114925. Available at: DOI:10.1016/j.applthermaleng.2020.114925
16. Vega Diaz R. Analysis of an Electric Environmental Control System to Reduce the Energy Consumption of Fxed-Wing and Rotary-Wing Aircraft. Cranfield University; 2011. Available at: https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/7422/Rolando_Vega_Diaz_Thesis_2011.pdf?sequence=1&isAllowed=y
17. Devadurgam H., Rajagopal S., Munjulury RC. Analytical Desgin and Estimation of Conventional and Elctrical Aircraft Environmental Control System. : 1–14. Available at: DOI:10.31224/osf.io/gu4pz
18. Genty A., Saunders A., Cimino JP., Rose S. Environmental Control System for Light Turbo Prop. 33rd International Conference On Environmental Systems. SAE International; 2003. pp. 1–9. Available at: DOI:10.4271/2003-01-2400
19. Shang Y., Wang J., Bi Y., Jian Y., Pei Y., Yuan W., et al. Air

- dehumidification by membrane with cold water for manned spacecraft environmental control. MATEC Web of Conferences. 2017; 114: 1–7. Available at: DOI:10.1051/matecconf/201711402011
20. Jonsson G., Palsson OP. An application of extended kalman filtering to heat exchanger models. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*. 1994; 116(2): 257–264. Available at: DOI:10.1115/1.2899218
 21. Najjar N., Gupta S., Hare J., Kandil S., Walthall R. Optimal sensor selection and fusion for heat exchanger fouling diagnosis in aerospace systems. *IEEE Sensors Journal*. 2016; 16(12): 4866–4881. Available at: DOI:10.1109/JSEN.2016.2549860
 22. Palmer KA., Hale WT., Such KD., Shea BR., Bollas GM. Optimal design of tests for heat exchanger fouling identification. *Applied Thermal Engineering*. Elsevier Ltd; 2016; 95: 382–393. Available at: DOI:10.1016/j.applthermaleng.2015.11.043
 23. Pang L., Qu H., Dong S. Fault diagnosis algorithm for heat exchanger of aircraft environment control system based on double model filter. *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*. 2008; 29(3): 548–553.
 24. Wright S., Andrews G., Sabir H. A review of heat exchanger fouling in the context of aircraft air-conditioning systems, and the potential for electrostatic filtering. *Applied Thermal Engineering*. 2009. pp. 2596–2609. Available at: DOI:10.1016/j.applthermaleng.2009.01.002
 25. Shang L., Liu G. Aircraft Heat Exchanger fouling detection based on valve control command. *Journal of Aerospace*. 2012; 226(7): 740–750. Available at: DOI:doi: 10.1177/0954410011416058
 26. Cubillo A. PHYSICS-BASED APPROACH TO DETECT METAL-METAL CONTACT IN THE HYDRODYNAMIC BEARING OF A PLANETARY TRANSMISSION. Cranfield University; 2016.
 27. Eker Ö. A Hybrid Prognostic Methodology and its Application to

WellControlled Engineering Systems. Cranfield University; 2015.

28. Byington CS., Watson M., Edwards D., Stoelting P. A model-based approach to prognostics and health management for flight control actuators. IEEE Aerospace Conference Proceedings. 2004; 6: 3551–3562. Available at: DOI:10.1109/AERO.2004.1368172
29. Jennions I., Ali F. Assessment of Heat Exchanger Degradation in a Boeing 737-800 Environmental Control System. Journal of Thermal Science and Engineering Applications. 1 December 2021; 13(6). Available at: DOI:10.1115/1.4050324
30. Butler S. Prognostic Algorithms for Condition Monitoring and Remaining Useful Life Estimation. NATIONAL UNIVERSITY OF IRELAND, MAYNOOTH; 2012. Available at: <http://core.kmi.open.ac.uk/download/pdf/11527019.pdf>
31. Isermann R. Model-based fault-detection and diagnosis - Status and applications. Annual Reviews in Control. 2005; 29(1): 71–85. Available at: DOI:10.1016/j.arcontrol.2004.12.002
32. Jonsson GR., Lalot S., Palsson OP., Desmet B. Use of extended Kalman filtering in detecting fouling in heat exchangers. International Journal of Heat and Mass Transfer. 2007; 50: 2643–2655. Available at: DOI:10.1016/j.ijheatmasstransfer.2006.11.025
33. Shah S., Liu G., Greatrix DR. On-line fouling detection of aircraft environmental control system cross flow heat exchanger. 2009 IEEE International Conference on Mechatronics and Automation, ICMA 2009. 2009. pp. 2940–2945. Available at: DOI:10.1109/ICMA.2009.5246062
34. Ma J., Lu C., Liu H. Fault diagnosis for the heat exchanger of the aircraft environmental control system based on the strong tracking filter. PLoS ONE. 2015; 10(3): 1–11. Available at: DOI:10.1371/journal.pone.0122829
35. Mutambara AGO., Al-Haik MSY. EKF based parameter estimation for a heat exchanger. Proceedings of the American Control Conference. 1999; 6(June): 3918–3922. Available at: DOI:10.1109/acc.1999.786251

36. Hu G., Gao S., Zhong Y., Gao B., Subic A. Modified strong tracking unscented Kalman filter for nonlinear state estimation with process model uncertainty. *International Journal of Adaptive Control and Signal Processing*. 2015; 29(12): 1561–1577. Available at: DOI:10.1002/acs.2572
37. Ding SX. *Model-Based Fault Diagnosis Techniques*. Second. Springer. London: Springer London; 2013. Available at: DOI:10.1007/978-1-4471-4799-2
38. Wang S., Wang JB. Robust sensor fault diagnosis and validation in HVAC systems. *Transactions of the Institute of Measurement and Control*. 2002; 24(3): 231–262. Available at: DOI:10.1191/0142331202tm030oa
39. Rajaraman S., Hahn J., Mannan MS. A Methodology for Fault Detection, Isolation, and Identification for Nonlinear Processes with Parametric Uncertainties. *Industrial & Engineering Chemistry Research*. 2004; 43(21): 6774–6786. Available at: DOI:10.1021/ie0400806
40. Daigle MJ., Goebel K. A Model-Based Prognostics Approach Applied to Pneumatic Valves. *International Journal of Prognostics and Health Management*. 2011; 2: 1–16.
41. Daigle M., Goebel K. Model-based prognostics under limited sensing. *IEEE Aerospace Conference Proceedings*. 2010; Available at: DOI:10.1109/AERO.2010.5446822
42. Yu Y., Woradechjurnroen D., Yu D. A review of fault detection and diagnosis methodologies on air-handling units. *Energy and Buildings*. 2014; 82: 550–562. Available at: DOI:10.1016/j.enbuild.2014.06.042
43. Mostofi M., Shamekhi AH., Ziabasharhagh M. Developing an algorithm for si engine diagnosis using parity relations. *American Society of Mechanical Engineers, Dynamic Systems and Control Division (Publication) DSC*. 2006; (March 2014). Available at: DOI:10.1115/IMECE2006-13463
44. Varrier S., Koenig D., Martinez JJ. A parity space-based fault detection on LPV systems: Approach for vehicle lateral dynamics control system. *IFAC Proceedings Volumes (IFAC-PapersOnline)*. 2012. pp. 1191–1196.

Available at: DOI:10.3182/20120829-3-MX-2028.00053

45. Hwang W., Huh K. Fault Detection and Estimation for Electromechanical Brake Systems Using Parity Space Approach. *Journal of Dynamic Systems, Measurement, and Control*. 2015; 137(1): 014504. Available at: DOI:10.1115/1.4028184
46. Laamami S., Ben HM., Sbita L. Fault detection for nonlinear systems: Parity space approach. *Information Technology and Computer Applications Congress (WCITCA), 2015 World Congress on*. 2015; (5): 1–5. Available at: DOI:10.1109/WCITCA.2015.7367055
47. Zhirabok AN. Parity space approach to fault diagnosis in nonlinear systems. *European Control Conference, ECC 1999 - Conference Proceedings*. 1999. pp. 232–235. Available at: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84930599543&partnerID=tZOtx3y1>
48. El-Mezyani T., Düştögör D., ... Parity space approach for enhanced fault detection and intelligent sensor network design in power systems. *Power and Energy* 2010; : 1–8. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5590102
49. Yin S., Huang Z. Performance Monitoring for Vehicle Suspension System via Fuzzy Positivistic C-Means Clustering Based on Accelerometer Measurements. *IEEE/ASME Transactions on Mechatronics*. IEEE; 2015; 20(5): 2613–2620. Available at: DOI:10.1109/TMECH.2014.2358674
50. Yin S., Li X., Gao H., Kaynak O. Data-based techniques focused on modern industry: An overview. *IEEE Transactions on Industrial Electronics*. IEEE; 2015; 62(1): 657–667. Available at: DOI:10.1109/TIE.2014.2308133
51. Najjar N., Hare J., D'Orlando P., Leaper G., Pattipati K., Silva A., et al. Heat Exchanger Fouling Diagnosis for an Aircraft Air-Conditioning System. *SAE International*. 2013; Available at: DOI:10.4271/2013-01-2250
52. Littooy B., Loire S., Georgescu M., Mezi I. Pattern Recognition and Classification of HVAC Rule-Based Faults in Commercial Buildings. 2016;

- : 1412–1421. Available at: DOI:10.1109/BigData.2016.7840749
53. Skliros C., Ali F., King S., Jennions I. Aircraft system-level diagnosis with emphasis on maintenance decisions. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 26 October 2021; : 1748006X2110549. Available at: DOI:10.1177/1748006X211054938
 54. Leondes CT. Expert systems: the technology of knowledge management and decision making for the 21st century. 2002. 1–22 p.
 55. Bruton K., Raftery P., Kennedy B. Review of automated fault detection and diagnostic tools in air handling units. 2014; : 335–351. Available at: DOI:10.1007/s12053-013-9238-2
 56. Zadeh LA. Fuzzy sets. Information and Control. June 1965; 8(3): 338–353. Available at: DOI:10.1016/S0019-9958(65)90241-X
 57. Adhikari S., Sinha N., Dorendrajit T. Fuzzy logic based on-line fault detection and classification in transmission line. SpringerPlus. 2016. Available at: DOI:10.1186/s40064-016-2669-4
 58. Liu XF., Dexter A. Fault-tolerant supervisory control of VAV air-conditioning systems. Energy and Buildings. 2001; 33(4): 379–389. Available at: DOI:10.1016/S0378-7788(00)00120-1
 59. Najafi M., Auslander DM., Bartlett PL., Haves P., Sohn MD. Application of machine learning in the fault diagnostics of air handling units. Applied Energy. Elsevier Ltd; 2012; 96: 347–358. Available at: DOI:10.1016/j.apenergy.2012.02.049
 60. Teodosiu C., Pastravanu O., Macoveanu M. Neural network models for ultrafiltration and backwashing. Water Research. 2000; 34(18): 4371–4380. Available at: DOI:10.1016/S0043-1354(00)00217-7
 61. Riverol C., Napolitano V. Estimation of the overall heat transfer coefficient in a tubular heat exchanger under fouling using neural networks. Application in a flash pasteurizer. International Communications in Heat and Mass Transfer. 2002; 29(4): 453–457. Available at:

DOI:10.1016/S0735-1933(02)00342-1

62. Riverol C., Napolitano V. Estimation of fouling in a plate heat exchanger through the application on neural networks. *Journal of Chemical Technology and Biotechnology*. 2005; 80(5): 594–600. Available at: DOI:10.1002/jctb.1198
63. Hare J., Gupta S., Najjar N., Orlando PD., Walthall R. System-Level Fault Diagnosis with Application to the Environmental Control System of an Aircraft. 2015; Available at: DOI:10.4271/2015-01-2583.Copyright
64. Allen WH., Member S., Rubaai A., Chawla R. Fuzzy Neural Network-Based Health Monitoring for HVAC System Variable-Air-Volume Unit. *IEEE Transactions on Industry Applications*. IEEE; 2016; 52(3): 2513–2524. Available at: DOI:10.1109/TIA.2015.2511160
65. Du Z., Fan B., Jin X., Chi J. Fault detection and diagnosis for buildings and HVAC systems using combined neural networks and subtractive clustering analysis. *Building and Environment*. Elsevier Ltd; 2014; 73: 1–11. Available at: DOI:10.1016/j.buildenv.2013.11.021
66. Lee K-P., Wu B-H., Peng SMU in MRRR fault detection and diagnosis of air-handling units _ EER pdfh.-L. Deep-learning-based fault detection and diagnosis of air-handling units. *Building and Environment*. 2019; 157. Available at: DOI:10.1016/j.buildenv.2019.04.029
67. Berkeley L. Comparison of Chiller Models for Use in Model-Based Fault Detection Priya Sreedharan and Phil Haves. 2001; (June).
68. Yu B., Van Paassen DHC., Riahy S. General modeling for model-based FDD on building HVAC system. *Simulation Practice and Theory*. 2002; 9(6–8): 387–397. Available at: DOI:10.1016/S1569-190X(02)00062-X
69. Buswell RA., Norford LK., Klaassen CJ., Luo D., Wright JA., Suby A. Demonstration of Fault Detection and Diagnosis Methods for Air-Handling Units. *HVAC&R Research*. 2011; 8(1): 41–71. Available at: DOI:10.1080/10789669.2002.10391289
70. Isermann R. Process fault detection based on modeling and estimation

- methods-A survey. *Automatica*. 1984; 20(4): 387–404. Available at: DOI:10.1016/0005-1098(84)90098-0
71. Yang X Bin., Jin XQ., Du ZM., Zhu YH. A novel model-based fault detection method for temperature sensor using fractal correlation dimension. *Building and Environment*. Elsevier Ltd; 2011; 46(4): 970–979. Available at: DOI:10.1016/j.buildenv.2010.10.030
 72. Santos APP., Andrade CR., Zaparoli EL. A thermodynamic study of air cycle machine for aeronautical applications. *International Journal of Thermodynamics*. 2014; 17(3): 117–126. Available at: DOI:10.5541/ijot.538
 73. Scholz D., Giese T., Erdmann C. Flecs: Functional Library of the Environmental Control System – a Simulation Tool for the Support of Industrial Processes. AST 2007, March 29-30, Hamburg, Germany. 2007.
 74. C. Müller, D. Scholz TG. Dynamic Simulation of Innovative Aircraft Air Conditioning. 1st CEAS European Air and Space Conference. 2007. pp. 869–878.
 75. Tu Y., Lin G. Dynamic Simulation of Humid Air Environmental Control System. 40th International Conference on Environmental Systems. 2010. pp. 1–10. Available at: DOI:10.2514/6.2010-6305
 76. Lang X., Li P., Hu Z., Ren H., Li YAN. Leak Detection and Location of Pipelines Based on LMD and Least Squares Twin Support Vector Machine. 2017; : 8659–8668.
 77. Burroughs JD., Hammond RA. Control Analysis and Design Features of EASY5. American Control Conference. San Francisco; 1983. pp. 58–63. Available at: DOI:10.23919/ACC.1983.4788072
 78. Hoffman G. Environmental Control System Simulation using EASY5, as Applied to the F-14,. Intersociety Conference on Environmental Systems. 1985. p. 8.
 79. Schooley C. A Time-response Analysis of an Air Distribution Subsystem of an Aircraft Environmental Control System Using MSC Easy5 TM.

- MSC.Software VPD Conference. 2006.
80. Karlsson J. Diagnosis of the air distribution system of the JAS39 Gripen environmental control system. Linköping Institute of Technology; 2001.
 81. Steinkellner S., Andersson H., Gavel H., Krus P. Modeling and Simulation of Saab Gripen's Vehicle Systems. AIAA Modeling and Simulation Technologies Conference. Reston, Virginia: American Institute of Aeronautics and Astronautics; 2009. pp. 1–15. Available at: DOI:10.2514/6.2009-6134
 82. Steinkellner S. Aircraft vehicle systems modeling and simulation under uncertainty. LINKÖPING University; 2011.
 83. Sielemann M. Device-Oriented Modeling and Simulation in Aircraft Energy Systems Design. Technischen Universität Hamburg-Harburg; 2012.
 84. Romani R., De Goes LC. Cabin Temperature Control Model for Commercial Aircraft. Modeling and Simulation Technologies Conference. 2012; (August): 1–15. Available at: DOI:10.2514/6.2012-4637
 85. Escobar IC. Condition Monitoring For Environmental Control Systems. Cranfield University; 2015.
 86. Figueroa DV. Diagnostic Capability for Environmental Control Systems. Universidad Politécnica de Madrid, Cranfield University; 2017.
 87. Scott M. Development of a Realistic, Automated, & Efficient Reliability Development Growth Test for a Large, Distributed, Environmental Control System. SAE Technical Paper Series. 1999. Available at: DOI:10.4271/1999-01-2165
 88. Fourquet H., Taillepied D., Novo N., Rolland A. Performance Validation of a New Water Separator Concept. 30th International Conference on Environmental Systems. SAE Technical Paper; 2000. Available at: DOI:10.4271/2000-01-2269
 89. Childs T., Jones AB., Chen R. Development of a Full Scale Experimental and Simulation Tool for Environmental Control System Optimisation and

- Fault Detection. 2015; : 0–11. Available at: DOI:10.2514/6.2015-1196
90. Childs TG., Jones AB., Chen R., Murray A. Evaluating Environmental Control System Thermal Response to Degraded Operating Conditions. 2016; : 0–16. Available at: DOI:10.2514/6.2016-1151
 91. Childs T., Jones A., Chen R., Murray A. A study into refrigeration cycle working fluids using an air cycle machine environmental control system. 54th AIAA Aerospace Sciences Meeting. 2016; 0: 0–14. Available at: DOI:10.2514/6.2016-2190
 92. Esperon-Miguez M., Jennions IK., Escobar IC., Hanov N. Simulating faults in a Boeing 737-200 Environmental Control System using a thermodynamic model. *International Journal of Prognostics and Health Management*. 1 June 2019; 10(2): 1–12. Available at: DOI:10.36001/ijphm.2019.v10i2.2731

3 A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics

‘There are many ways of going forward, but only one way of standing still.’

- Franklin D. Roosevelt

The Environmental Control System (ECS) of an aircraft is responsible for regulating and conditioning the airflow into the cockpit, cabin and avionics bay. The ECS is composed of several complex sub-systems and components that are reported as key unscheduled maintenance drivers for legacy aircraft by aircraft operators. Furthermore, the incorporated temperature and flow control valves in these sub-systems have the capability to mask potential faults at the component level, making the diagnostic process very challenging. To overcome this challenge, the aviation industry is currently proactively exploring the predictive maintenance approach that allows real-time monitoring of the key systems, sub-systems and components. In the context of the ECS, this necessitates the requirement to equip the system with appropriate condition monitoring capabilities. To do this, the performance characteristics of the ECS at sub-system and component level needs to be well understood under a wide-range of aircraft operating scenarios. Existing literature provides component level and system level analyses of the ECS. However, it lacks an experimentally verified and validated ECS sub-system and component level simulation tool (ECS Digital Twin), capable of simulating the thermodynamic performance and component health state parameters under wide-ranging aircraft operational scenarios. The ECS Digital Twin (DT) developed by the Cranfield University IVHM Centre offers the capability to simulate healthy and faulty cases of the Passenger Air Conditioner (PACK). This chapter proposes a methodology for full-scale experimental Verification & Validation (V&V) of the developed ECS DT, to enable component level simulation, and enabling accurate diagnostics, of the civil aircraft ECS.

Note that, the methodology highlighted in section 3.4 has evolved as the PhD progressed and the final version of the methodology is highlighted in Section 1.4. The fault injection experimental investigation plans have also been replaced with the plan to study humidity at the later stage of the PhD. All these changes are highlighted as footnote within the text.

Table 3-1, shows the table of content of this chapter. This chapter has been published as a conference paper in the annual conference of the Prognostics and Health Management Society 2019 (see list of publications in section 1.6).

Table 3-1 Overview of Chapter 3

3.1	Introduction
3.2	Aircraft Maintenance
3.3	Environmental Control System
3.4	Verification & Validation Process
3.5	Experimental Setup
3.6	Simulation Results
3.7	Conclusion

3.1 Introduction

The ECS of an aircraft regulates the supply of conditioned airflow throughout the cabin. The overall ECS is composed of several complex subsystems that are prone to degradation and can, therefore, lead to failure, compromising the system functionality and increased unscheduled maintenance activity. This leads to the ECS being a major driver for maintenance and necessitates the requirement for identifying and developing a condition-based monitoring approach, enabling systematic diagnostics to minimise unscheduled maintenance as well as maximising system safety.

In this study, an experimentation plan has been designed and proposed to facilitate a comprehensive step-by-step V&V. The successful implementation of the proposed methodology ensures the acquisition of a robust experimental data set that is vital for enabling the development of a sophisticated diagnostic algorithm for fault detection and isolation of the ECS under a wide range of aircraft operational scenarios. Furthermore, the instrumentation set identified through the proposed methodology in terms of temperature, pressure, mass flow and humidity sensors allow a systematic understanding of the ECS performance characteristics and quantification of the ECS failure modes. This is necessary for the development of an effective model-based diagnostic rule for the ECS.

3.2 Aircraft Maintenance

In the aviation industry, manufacturers are required to ensure the continuing airworthiness of the aircraft, which includes maintenance, repair and overhaul, to maximise aircraft operational availability. The preventive maintenance process starts with regular checks, or in some cases with a fault report. As shown in Figure 3-1, after a certain number of flight hours, or once a fault is reported, the aircraft is grounded, and data is collected for diagnostic purposes. Based on the diagnostic results, maintenance plans are prepared. Once the desired maintenance activity is successfully implemented and verified, the aircraft is authorised to fly again. This type of approach generally leads to unnecessary downtime, impacting the aircraft availability, and therefore, leads to an increase in operating costs.

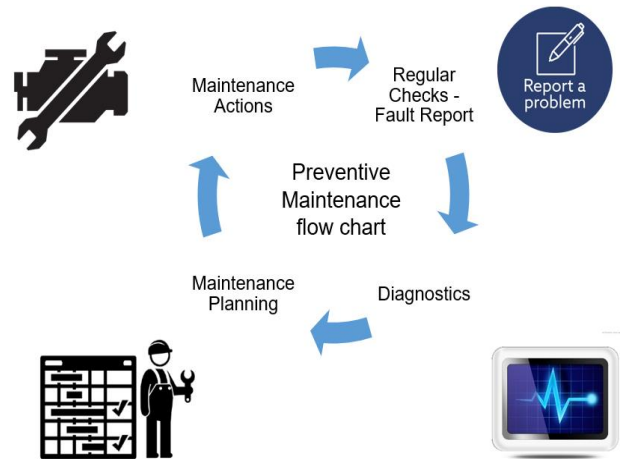


Figure 3-1 Preventive maintenance flow chart

To eliminate unnecessary maintenance costs, the aerospace industry is proactively exploring the shift towards predictive maintenance. This approach aims to replace the ‘Regular Checks’ step in Figure 3-1 with continuous condition monitoring to enable diagnosis based on the acquired real-time data. The data is further used to project estimation of the Remaining Useful Life (RUL) of the key sub-system; this information allows the determination of time between failures and therefore enables systematic and efficient planning of the required maintenance actions, necessary for achieving maximum aircraft operational availability and safety. Through this study, optimal sensor sets, and diagnostic rules will be explored.

3.2.1 Fault Detection and Isolation Approaches

In the past, different fault detection and isolation (FDI) capabilities have been extensively researched. These can be broadly categorised in three approaches: (i) Data-Driven [1], (ii) Model-based [2] and (iii) Hybrid [3]. Data-driven methods require a vast amount of data for extracting features and training FDI algorithms, as highlighted in research [4,5]. Researchers like Saxena and Saad [6] suggested the model-based approach to be ideal for complex systems such as the ECS with multiple fault modes. The model-based approach uses system dynamics and mathematical modelling to generate a residual outcome from the actual system and the simulation model output, providing a better understanding of the failure modes [7]. In the case of the ECS, fouling detection in the heat exchanger using

a model-based approach is reported using: extended Kalman filter [8] and double model filter [9]. Thus, based on the literature review, model-based diagnostic approach to detect fault occurrences in the ECS is targeted in this project.

3.2.2 ECS Digital Twin

Although the component-level condition monitoring has been widely researched, the open literature lacks exhaustive research work on a system-level approach. FLECS [10,11] is a system-level simulation platform for an ECS and contains healthy models of different ECS components. Test data (temperature readings) at the PACK outlet and the cabin were used to verify the model. Flowmaster [12,13] is another simulation package, verified against temperature readings that are collected through experimentation. Boeing's Easy5 [14] was used to model the ECS for both Civil and Military aircraft. However, systematic validation of the employed ECS model against experimentally acquired pressure, temperature and mass flow data has not been reported. With inspiration from Easy5, the Modelica programming language has been used to model an ECS in Dymola [15,16].

Amongst all these approaches, it has been identified that the experimental validation was not comprehensive and was dependent mostly on temperature readings collected at specific locations. To address this, the IVHM Centre has recently developed a digital twin for condition monitoring and diagnosis of the ECS [17], which will be validated based on the methodology proposed in this study. The salient features of the developed DT are:

- i. It provides a generic ECS component library, allowing the capability to simulate a wide-range of ECS design architectures.
- ii. It incorporates the ability to model degradation at the component level.
- iii. It allows the assessment of component-level design characteristics, system thermodynamics parameters, and humidity.

3.3 Environmental Control System

The ECS of an aircraft consists of three different complex subsystems to provide conditioned air with the correct temperature, pressure and humidity: (i) Bleed Air System (BAS), (ii) PACK and (iii) Air Distribution System (ADS). While the aircraft is in the air, bleed air from the engine compressor is used to power the ECS. On the ground, the ECS is driven by the Auxiliary Power Unit (APU). In both cases, the PACK regulates the thermodynamic parameters of the air. The airflow is then filtered and distributed to the cockpit, cabin and the avionics bay.

3.3.1 Passenger Air Conditioner

The PACK is the primary system for conditioning the flow within the ECS, which makes it the primary focus of this study. Figure 3-2 illustrates the schematic of a single PACK in the B737-400. It consists of Valves, Heat Exchangers, an Air-Cycle Machine (ACM) and a High-Pressure Water Separator (HPWS).

At the beginning of the PACK is the PACK valve (PV) that regulates airflow through the system. The PV controls airflow towards the Temperature Control Valves (TCV) and the core. The airflow splits into two streams: one enters the core through the Primary Heat Exchanger (PHX), and the other enters into the TCVs. The PHX allows for heat exchange between the hot compressed air from the engine compressor and the surrounding cold Ram air. The air then goes into the compressor of the ACM where the air is compressed, creating the pressure difference to drive the air through the system. The air further goes through the Secondary Heat Exchanger (SHX) which enables further heat exchange with the Ram air. The air then flows through the Reheater (RHX) and the Condenser (CHX). This drops the temperature further and initiates condensation of water droplets which are then drained out from the two Water Separators (WS). This part of the core is known as the HPWS. The RHX and CHX work as heat exchangers: the cold air from the WS outlet travels through the RHX, then further into the turbine. Energy is extracted from the air within the turbine to drive the compressor. As the temperature in the turbine outlet drops significantly, the two TCVs open and allow the hot bleed air to mix at the turbine-TCV merge. The cold air then flows through the CHX and out of the PACK.

The turbine inlet, compressor discharge and PACK discharge overheat switches controls the opening and closing of the valves. The PACK temperature sensor located at the outlet of the WS and the Ram air temperature sensor data is used by the aircraft zone temperature controller to regulate the PACK outlet temperature by varying the degree of valve opening.

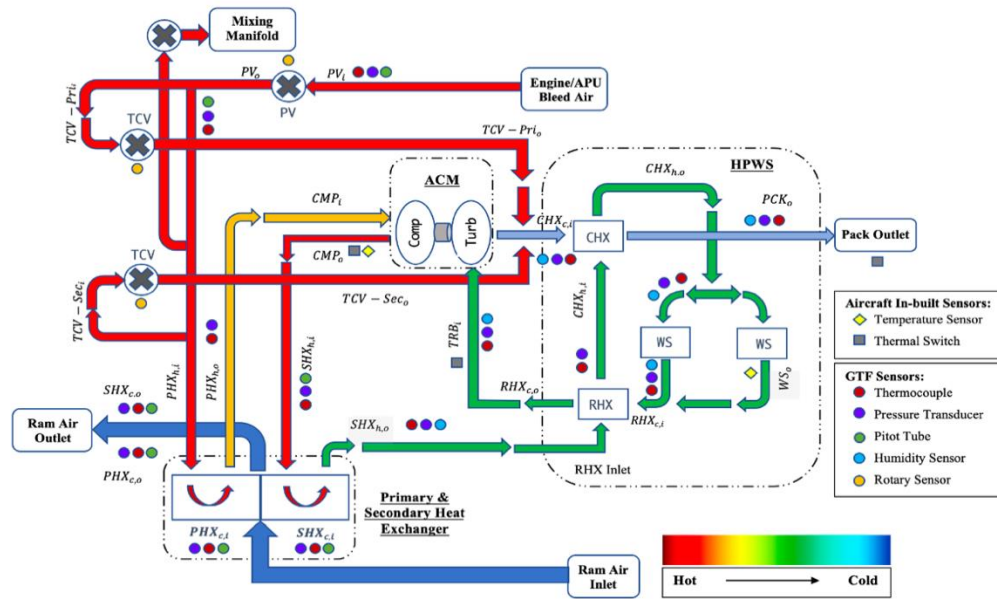


Figure 3-2 B737-400 PACK schematic with sensor installation

3.4 Verification & Validation Process

There is a compelling need to acquire comprehensive sets of data from the ECS systems for V&V of the DT developed at the IVHM Centre. Cranfield University's B737-400 will be used in this experiment to heavily instrument the ECS with sensors. This will allow a complete understanding of different fault modes within the ECS, which is essential for model-based FDI. Furthermore, the interdependencies between the components will also be analysed.

3.4.1 Methodology

This research work consists of 4 phases: literature review, experimental data, SESAC V&V, and write-up, as shown in Figure 3-3. To develop a ground test facility (GTF), the left-hand side PACK was removed from Cranfield's B737-400 aircraft. Sensors were selected, tested and installed. The sensor installation

locations are shown in Figure 3-2. With all the sensors installed, the PACK was refitted back in the aircraft. The sensors were all connected to a data acquisition unit (DAQ) inside the ECS bay.

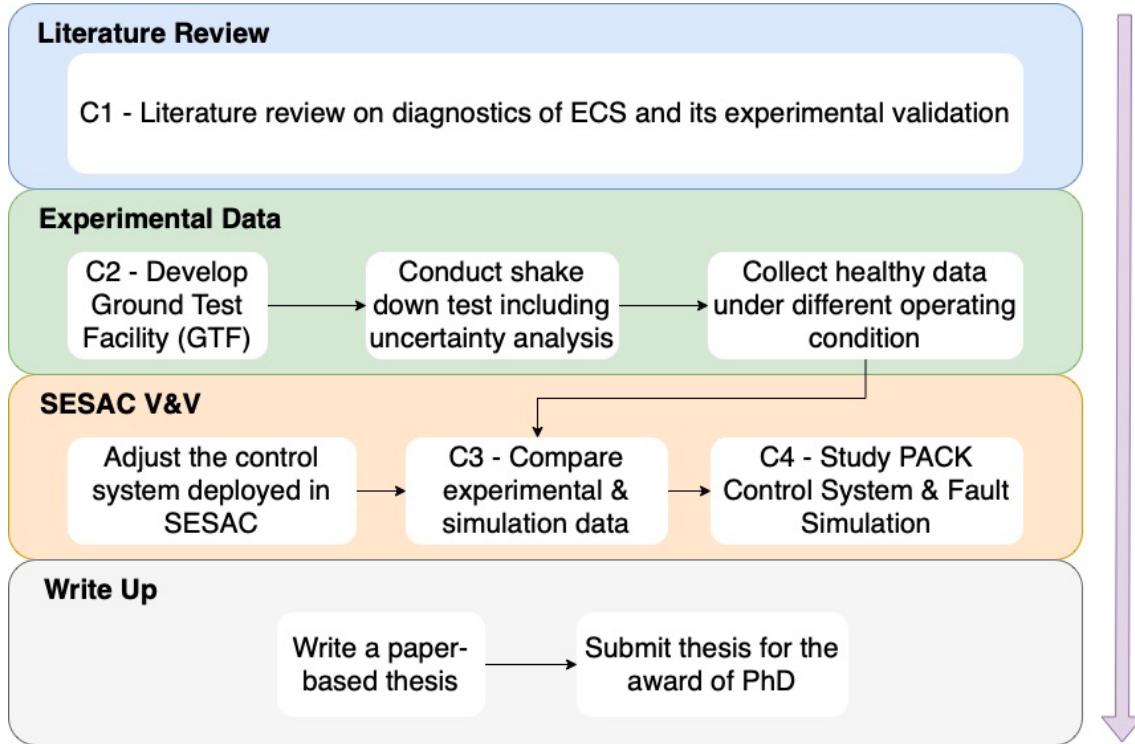


Figure 3-3 Research methodology

A simulation model for the designated ECS will be formed using the component library developed at the IVHM Centre. The sensor readings at the PV inlet (i.e. PACK inlet temperature, pressure, humidity and mass flow rate) will be treated as healthy and used as input parameters to the DT. The experimental data set, and simulation result will then be compared for V&V of the digital twin. The optimal sensor set for fault detection and diagnostic rules [18] will also be verified. If necessary, alterations will be made to the component library and ECS model. The control system governing PACK functionality will then be studied using experimental data. Finally, thermodynamic analysis of fault occurrences will be studied using simulation data collected from verified SESAC.

3.4.2 Simulation

The B737-400 model developed was initially calibrated by using the test cases provided by industrial partner The Boeing Company. Data collected from the model will include temperature, pressure, mass flow, valve angle and efficiency of the components (i.e. ACM, RHX, CHX, PHX, SHX). Once the healthy case results are achieved, fault simulation results will be analysed, starting with PHX degradation. Component degradation and failure modes are simulated as deviations in the health indicating parameters (e.g., decrease in heat exchanger effectiveness). Once the experimental data is collected, the model library will be calibrated to achieve an accurate model. Finally, the specific humidity and water content analysis capability will be incorporated in the model, which is a novel approach in investigating aircraft ECS.

3.4.3 Experimentation

As mentioned at the beginning of this section, all experimental work will be performed on Cranfield's B737-400 aircraft. All the experiments will be repeated under 2 different cabin zone temperature control setting (i.e. the individual temperature selectors at the cockpit, forward cabin and aft cabin will be set for the given cabin demand): (i) 18°C (cold) and (ii) 24°C (hot). The PACK consists of a trim valve which takes part of bleed mass flow from in between the two TCVs and mixes the hot air with the conditioned air at the mixing manifold. As the opening of trim valve can impact the PACK performance, the experimental data collection will include data that represents trim on and off conditions. Additionally data collected for Ram door scenario will be presented and discussed.

The average duration of each test has been estimated to be 10 minutes. This includes the time necessary to reach steady-state conditions, capture data, and the time necessary to start and shut down all the necessary systems of the aircraft. Within this time frame, thermodynamic parameters (pressure, temperature and mass flow), humidity and valve angular position will be recorded.

3.5 Experimental Setup

The left-hand side PACK from the B737-400 was removed from the aircraft. The ducts were dismantled and taken out, including the PV and TCVs. The ACM and HPWS came out as single units. The disassembled PACK is shown in Figure 3-4.



Figure 3-4 B737-400 Left-hand side PACK

Sensor bosses were then manufactured and welded onto the selected locations on the PACK. One of the restrictions with sensor selection was the availability of space for sensor installation. This means the angle at which the sensors are installed significantly impacts the final assembly process of the PACK. To accurately install the sensors, the locations were identified by referring to the

right-hand side PACK of the aircraft. Figure 3-5 shows the SHX inlet duct with a pressure transducer, thermocouple and total pressure head installed.



Figure 3-5 SHX inlet duct with sensors installed

3.5.1 Sensor Selection

Based on the previous studies on the ECS [18], operating temperature and pressure range throughout the system is estimated to be -33.15°C to $+186.85^{\circ}\text{C}$ and 100 KPa to 350 KPa. However, no previous data on the humidity was available. Thus, this experiment will be contributing directly to understanding the change in humidity within the HPWS. A total of 56 sensors have been installed, which will provide a clear understanding of the system performance characteristics.

Due to the high temperature in specific locations on the PACK, the sensors were carefully selected with a higher operating temperature range. For pressure sensors with a maximum functional limit at 125°C , temperature isolation coils were used to match the sensor installation temperature requirements. The k-type thermocouple was selected with a maximum temperature rating of $+400^{\circ}\text{C}$ to allow temperature measurements at the upper bound of the PACK operation. However, due to the design constraints associated with the humidity sensors for operating in higher temperature regions, the selection of installation locations was

carefully identified to comply with the sensor operating temperature range. Table 3-2 shows the breakdown of the number of sensors installed in the PACK.

Table 3-2 List of sensors installed in the PACK

Sensors	Quantity	Operating Temperature Range
Pressure Transducer	16	-40 to +125 °C
Intrusive Thermocouple	15	-100 to +400 °C
Non-intrusive thermocouple	8	-195.556 to +287.778 °C
Humidity Sensor	6	-40 to +85 °C
Rotary Sensor	3	+150 °C
Pitot-tube	8	-

3.5.2 Sensor Locations on the PACK

The sensors, selected in the previous section, were fitted at the inlet and the outlet of each component within the PACK. Due to the high temperature at the PACK inlet, humidity sensor could not be fitted in this region. They were also excluded from the RHX outlet (hot side) due to the spacing constraint. Therefore, the humidity sensors were only fitted at six locations from the HPWS inlet (through the RHX) to the PACK outlet.

Pressure and temperature sensors were installed throughout the PACK at the input and output of each component. In order to measure the mass flow through the system, pitot-tubes were fitted at eight different locations. These includes the PACK inlet, the PACK valve outlet (at the first split for the mass flow rate through TCV 1) and the Compressor outlet (for the mass flow rate through the core). The mass flow rate through the TCV 2 will be calculated by the mass flow readings from the existing pitot-tubes. The flow rate at the Ram air inlet door and the inlet and outlet through both PHX and SHX will also be recorded from the

pitot-tube fitted on these locations. The rotary sensors were installed on three valves: the PV and the two TCVs.

3.5.3 Sensor Tests

In order to avoid a non-functioning sensor being inadvertently fitted to the aircraft, all sensors were tested prior to installation. The pressure transducers were connected to a power supply of 5 VDC and grounded to test the electric connection and functionality of the sensors. The sensors were verified by measuring atmospheric pressure. The rotary sensors used to measure the valve angle were explicitly manufactured to measure a maximum of 90° clockwise rotation. With regards to the mass flow measurements, specifically tailored pitot-static tubes, were manufactured and tested using in-house capabilities at Cranfield's Gas Turbine Engineering Laboratory.

As shown in Figure 3-6, the humidity sensor was connected to a power supply. About 32% relative humidity was obtained at room temperature. The sensor was then held on top of steam (boiling water in the mug shown) to measure relative humidity. A reading of 98% relative humidity was obtained, thus verifying that the sensor is working.



Figure 3-6 An experimental test for relative humidity measurement of steam

The humidity sensor required a compression fitting, which uses a ferrule to seal the space between the sensor and the boss welded on the designated installation location. Figure 3-7 demonstrates the pressure test conducted on the humidity sensor to verify it's fitting.

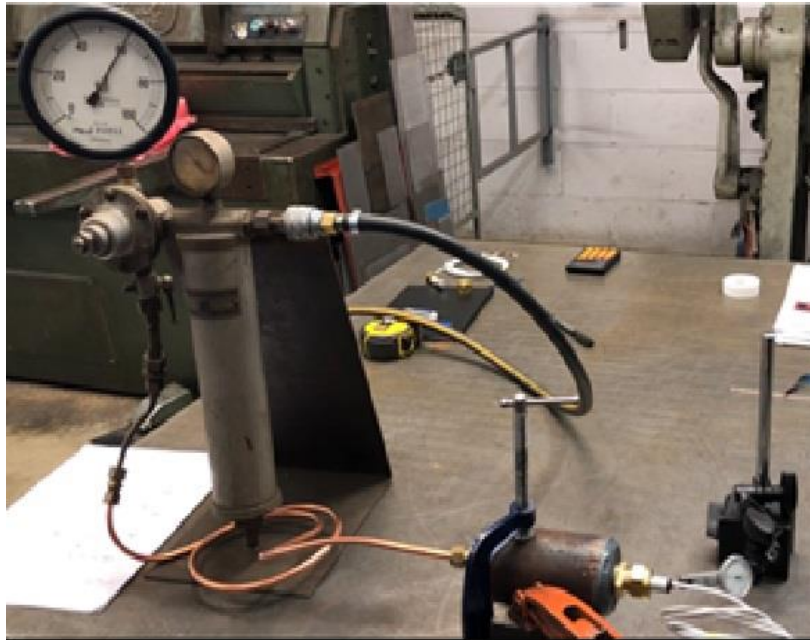


Figure 3-7 Experimental setup for compression fitting test on the humidity sensor

3.5.4 Ground Test Facility

The PACK was re-installed into the aircraft with all the sensors fitted in position. The ECS was powered by the APU for 10 minutes to conduct functionality test. The PACK was further tested for leakages, especially where sensor bosses were welded.

The cables from the sensors were connected into the DAQ and power supply to the sensors which were securely installed inside the ECS bay on a DIN rail. An ethernet cable from the DAQ was taken out and routed to the cabin through the landing gear inspection window, situated in the cabin floor. This way of connecting the sensors allows the ECS bay door to be closed and to have a lab environment inside the cabin to facilitate this research work and for future projects ensuring repeatability of the experiments, making this a unique GTF.

The DAQ includes voltage input modules (for pressure transducers, rotary sensors and humidity sensors) and temperature input modules (for thermocouples). As the experimental data will be collected at steady-state and at 1Hz, the voltage input modules and temperature input modules were selected with a minimum rating of 10 kHz and 50 Hz/ch respectively. The NI LabVIEW software package will be used for data acquisition and visual representation of the data being collected.

3.6 Simulation Results

In this section, the healthy and degraded case simulation results are presented and discussed, including a possible approach towards the development of the model-based diagnostic rule.

3.6.1 Healthy Case Simulation

An initial test run of the DT developed at the IVHM Centre was conducted at the ground condition. Table 3-3 shows the input parameters used to obtain simulation results. In the first simulation, the components (i.e. heat exchangers, ACM, CHX and RHX) were modelled to be in a healthy state.

Table 3-3 Input parameters for running simulation at ground level

Altitude	Ground
Mach	0
Bleed air temperature	188.1 °C
Bleed air pressure	305.024 kPa
Cabin target pressure	101.325 kPa
Cabin target temperature	15 °C
Cabin target mass flow	0.52 kg/s
Ram air temperature	23.889°C
Ram air mass flow	0.706 kg/s

The outputs – temperature, pressure and mass flow – across the PACK are graphically represented in Figure 3-8. The results represents the obtained simulated value at each output of the individual component of the system, and the dashed lines are added to obtain a visual representation of the temperature-

pressure profile throughout the PACK sub-systems. The model was not designed for any leakages in the ducts or the sub-systems of the PACK, and so this led to a constant mass flow rate through the system.

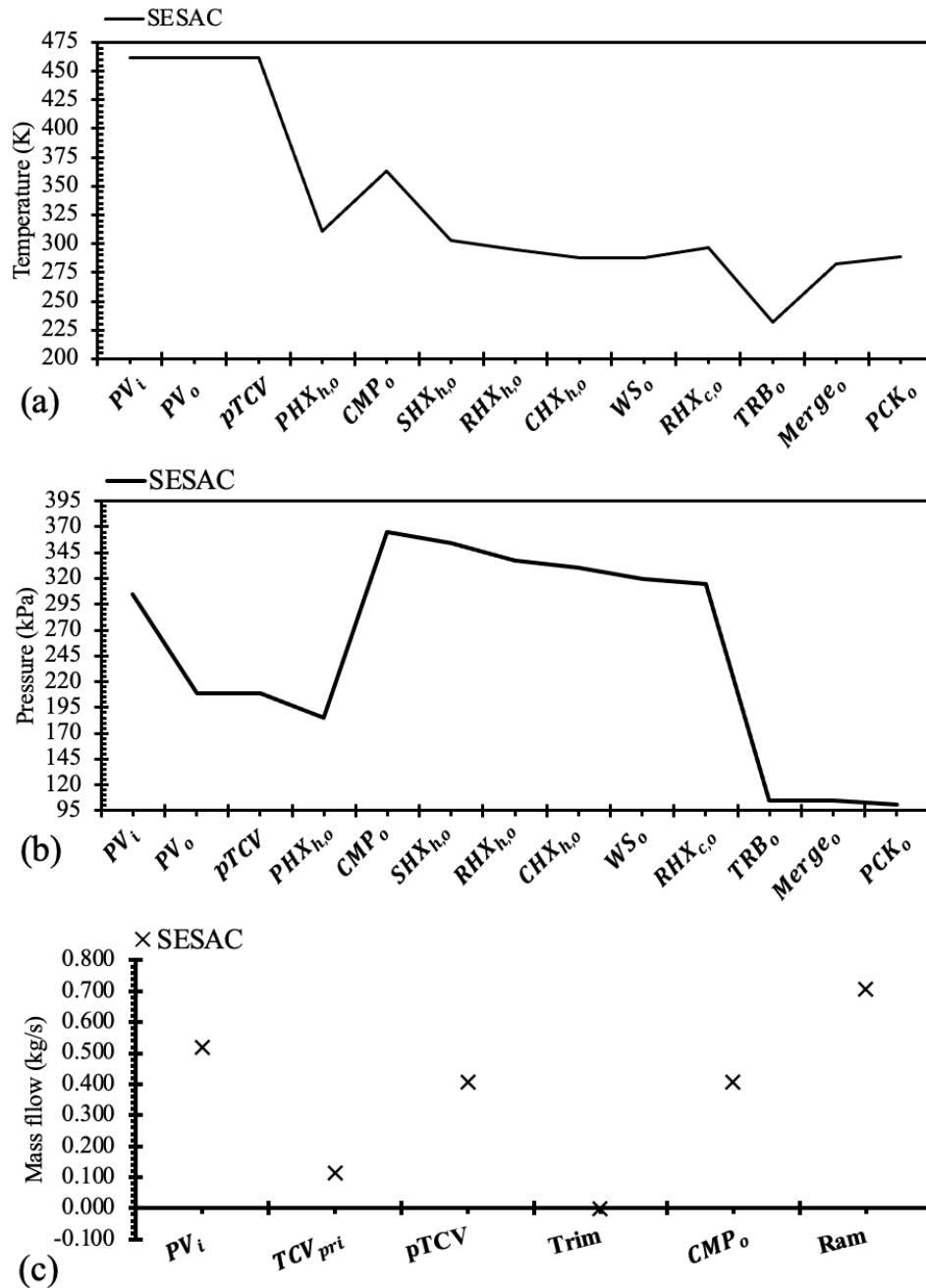


Figure 3-8 (a) Temperature profile, (b) Pressure profile and (c) Mass flow for healthy case

3.6.2 Fault Condition Simulation

In this section, the PHX degradation and its effect on the temperature and pressure profile are shown. For the input parameters as shown in Table 3-3, ten simulations were conducted with the PHX degradation severity level from 0 to 90% degraded with an increment of 10%. The temperature, pressure and mass flow profile obtained from the simulations are shown in Figure 3-9. In Figure 3-9(a), a gradual decrease in heat transfer across the PHX is noticed as the PHX was gradually degraded. Since the effectiveness of the PHX has dropped, the heat transfer rate was affected. The air then goes through the compressor, where a rise in temperature was noticed due to the compression of hot air. However, the SHX was noticed to work as an efficient heat sink to drastically drop the air temperature close to the target temperature. The SHX is observed to compensate for the effect of degradation in the PHX and is seen to maintain similar temperature at the $SHX_{h,o}$. Also, in Figure 3-9(c), it is noticed that the core mass flow drops and mass flow through the TCV increases as level of degradation increases. This suggests that the control system is gradually opening the valve to increase hot flow at the merge and subsequently dropping the core mass flow to meet the target temperature. This phenomenon, makes it evident that the control logic to drive the PV and TCV to regulate the temperature and pressure across the system is fundamental in achieving the target conditions. A detailed analysis of the fault occurrences are to be provided in this thesis for the heat exchangers and the valves.

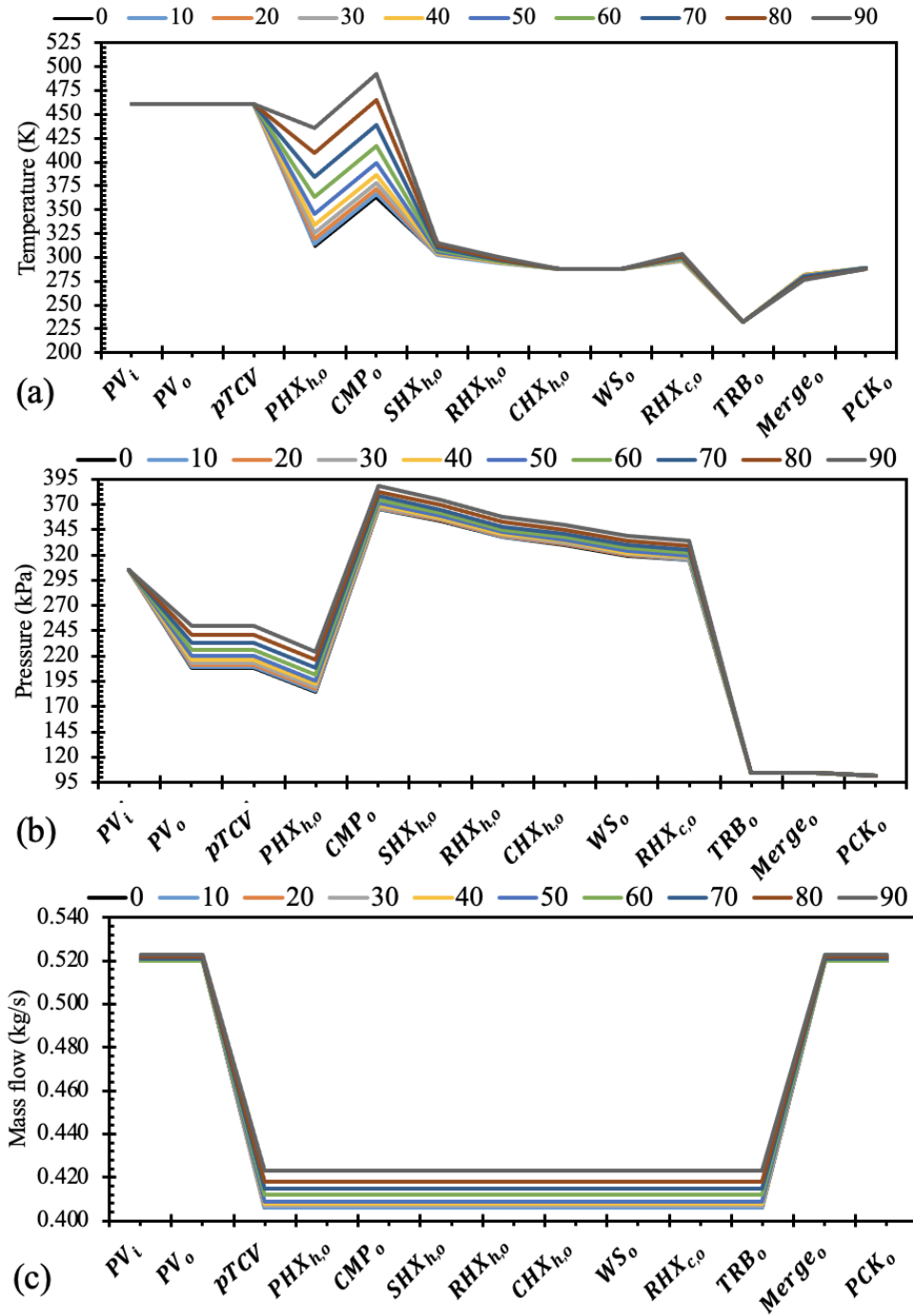


Figure 3-9 (a) Temperature profile, (b) Pressure profile and (c) Mass flow with PHX degradation severity from 0% healthy to 90% degraded

3.6.3 PACK Control System

The PACK control system utilises, a Pack Valve (PV), Temperature Control Valve (TCV) and a Trim valve to regulate the air across the system to achieve the target temperature. The valves opens and closes based on a number of temperature sensors and switches installed across the ECS. The regulations of the mass flow across the core of the PACK impacts the PACK performance. As highlighted the previous section, the PACK controls the valves in cases of a fault occurrence to main target temperature at the cabin. Therefore, it is understood that the control system plays a significant role in the PACK performance and requires to be studied. The experimental data collected will be used to understand the control system functional behaviour of the PACK and if necessary, the control login deployed within SESAC will be fine-tuned. Furthermore, PV and TCV fault occurrence will be analysed and discussed using simulation data.

3.7 Conclusion

This chapter proposes a methodology targeting the full-scale cost-effective experimental testing and V&V of a civil aircraft ECS DT at the component level. Although the experimental work will be on the ground, as the DT is physics-based, the successful implementation of the devised methodology is seen as an essential first step in the development of a robust ECS DT, capable of performing a comprehensive evaluation of the ECS performance. This will also enable the development of fault detection and isolation capability for the ECS PACK. The experimental plan for acquiring the system thermodynamic performance data in terms of pressure, temperature, mass flow under a wide-range of ECS healthy and faulty operational scenarios has been identified and elaborated. The selection of the required instrumentation set for experimental rig setup in terms of pressure, temperature, mass flow and humidity sensors has been described. The requirements for the sensor installation, calibration and test have also been discussed and illustrated. An initial ground test case was simulated for both healthy and PHX degraded cases are shown in this chapter. It is identified that by simulating and experimentally verifying the simulation results can be used to develop a model-based diagnostic rule to detect and isolate faults in the ECS

PACK. This combination of the GTF and a verified DT will open doors to numerous possibilities of formulating innovative IVHM technologies, enabling cost-effective maintainability of civil aircraft ECS systems.

References

1. Lightfoot H., Greenough RM. State-of-the-art in integrated vehicle health management. 2016; (March): 1–14. Available at: DOI:10.1243/09544100JAERO446
2. Cubillo A., Perinpanayagam S., Esperon-Miguez M. A review of physics-based models in prognostics: Application to gears and bearings of rotating machinery. *Advances in Mechanical Engineering*. 26 August 2016; 8(8): 168781401666466. Available at: DOI:10.1177/1687814016664660
3. Jung D., Ng KY., Frisk E., Krysander M. Combining model-based diagnosis and data-driven anomaly classifiers for fault isolation. *Control Engineering Practice*. Elsevier Ltd; 2018; 80(September): 146–156. Available at: DOI:10.1016/j.conengprac.2018.08.013
4. Yang X Bin., Jin XQ., Du ZM., Zhu YH. A novel model-based fault detection method for temperature sensor using fractal correlation dimension. *Building and Environment*. Elsevier Ltd; 2011; 46(4): 970–979. Available at: DOI:10.1016/j.buildenv.2010.10.030
5. Daigle MJ., Goebel K. A Model-Based Prognostics Approach Applied to Pneumatic Valves. *International Journal of Prognostics and Health Management*. 2011; 2: 1–16.
6. Saxena A., Saad A. Evolving an artificial neural network classifier for condition monitoring of rotating mechanical systems. *Applied Soft Computing Journal*. 2007; 7(1): 441–454. Available at: DOI:10.1016/j.asoc.2005.10.001
7. Butler S. Prognostic Algorithms for Condition Monitoring and Remaining Useful Life Estimation. NATIONAL UNIVERSITY OF IRELAND, MAYNOOTH; 2012. Available at:

<http://core.kmi.open.ac.uk/download/pdf/11527019.pdf>

8. Jonsson GR., Lalot S., Palsson OP., Desmet B. Use of extended Kalman filtering in detecting fouling in heat exchangers. *Interantional Journal of Heat and Mass Transfer*. 2007; 50: 2643–2655. Available at: DOI:10.1016/j.ijheatmasstransfer.2006.11.025
9. Pang L., Qu H., Dong S. Fault diagnosis algorithm for heat exchanger of aircraft environment control system based on double model filter. *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*. 2008; 29(3): 548–553.
10. Scholz D., Giese T., Erdmann C. Flecs: Functional Library of the Environmental Control System – a Simulation Tool for the Support of Industrial Processes. *AST 2007*, March 29-30, Hamburg, Germany. 2007.
11. C. Müller, D. Scholz TG. Dynamic Simulation of Innovative Aircraft Air Conditioning. 1st CEAS European Air and Space Conference. 2007. pp. 869–878.
12. Tu Y., Lin G. Dynamic Simulation of Humid Air Environmental Control System. 40th International Conference on Environmental Systems. 2010. pp. 1–10. Available at: DOI:10.2514/6.2010-6305
13. Tu Y., Lin GP. Dynamic Simulation of Aircraft Environmental Control System Based on Flowmaster. *Journal of Aircraft*. 2011; 48(6): 2031–2041. Available at: DOI:10.2514/1.C031433
14. Burroughs JD., Hammond RA. Control Analysis and Design Features of EASY5. *American Control Conference*. San Francisco; 1983. pp. 58–63. Available at: DOI:10.23919/ACC.1983.4788072
15. Steinkellner S., Andersson H., Gavel H., Krus P. Modeling and Simulation of Saab Gripen's Vehicle Systems. *AIAA Modeling and Simulation Technologies Conference*. Reston, Virigina: American Institute of Aeronautics and Astronautics; 2009. pp. 1–15. Available at: DOI:10.2514/6.2009-6134

16. Steinkellner S. Aircraft vehicle systems modeling and simulation under uncertainty. LINKÖPING University; 2011.
17. Escobar IC. Condition Monitoring For Environmental Control Systems. Cranfield University; 2015.
18. Figuero DV. Diagnostic Capability for Environmental Control Systems. Universidad Politécnica de Madrid, Cranfield University; 2017.

4 A Novel Boeing 737 Ground Test Facility for the Experimental Investigation of a Civil Aircraft ECS

‘It is the weight, not numbers of experiments that is to be regarded.’

- Isaac Newton

The aircraft Environmental Control System (ECS) is a highly integrated and complex system. The passenger air conditioner (PACK) is the heart of the ECS that conditions bleed air prior to supplying it to the cabin and avionics bay. The PACKs capability to mask fault occurrences has resulted in increased unscheduled maintenance of the system. As such it has been a key research topic to understand PACK performance characteristics in order to support an accurate diagnostic solution. It has been identified from the literature review that the existing literature lacks a comprehensive experimental investigation of the ECS PACK performance characteristics and verification of an existing simulation model that can be used for developing model-based diagnostic solution. The development of such accurate diagnostic solution would identify the degradation early and hence support effective maintenance and reduce cost. This chapter is a continuation of the authors' work on the development of a systematically derived PACK simulation model (SESAC) where the development of a Boeing 737 Ground Test Facility (GTF) is reported for performing experimental analysis on PACK performance under various PACK operating and ambient conditions. A discussion on the employed sensors uncertainty is outlined based on laboratory tests. The data collected under different temperature demands and operating modes are compared against simulation. The overall investigation suggests a reasonably good match between experimental and simulation data. It has been identified that the control system plays a significant role in impacting the PACK performance, for which an end-to-end ECS instrumentation and experimental analysis is deemed to be necessary for supporting accurate simulation and diagnostics of the ECS.

Table 4-1 shows the table of content of this chapter. This chapter is submitted to the Journal of Applied Thermal Engineering and is currently under review process.

Table 4-1 Overview of Chapter 4

4.1	Introduction
4.2	Background - Overview of PACK Operation and SESAC
4.3	Development of the B737-400 Ground Test Facility
4.4	Uncertainty Analysis
4.5	GTF Experimental Validation
4.6	Comparison of SESAC Against the SESAC Simulation
4.7	Summary and Conclusions

4.1 Introduction

The Environmental Control System (ECS) provides pressurised air to the anti-ice system and regulates cabin temperature (T), pressure (P) and humidity (RH). To serve its purpose, it utilises: (i) Bleed Air System (BAS), (ii) Passenger Air Conditioner (PACK) and (iii) Air Distribution System (ADS). The PACK is the core module of the ECS and consists of various components which are prone to degradation [1].

To maximise aircraft operational availability by providing fleet care, the original equipment manufacturers are actively working on improving diagnostic tools to help minimise maintenance costs. The Boeing company has reported the Environmental Control System (ECS) of legacy aircraft such as the Boeing 737 to be one of the major drivers for maintenance which demands cost-effective and accurate diagnostic solutions [1]. The diagnostics of such ECS systems becomes challenging due to the lack of data that can be used to study fault occurrences and their propagation. In addition to that, the capability of the flow control valves

to mask fault occurrences makes the diagnostic process even more challenging. It is necessary to understand PACK performance under different operating conditions, including the fault occurrences and, consequently, its impact on the overall PACK performance characteristics. This knowledge will allow identification of component health state indicating parameters that can support the development of effective diagnostic tools.

Analysing PACK performance has led to a number of research initiatives [2–7]. The literature suggests that component level performance assessment has been mostly targeted towards heat exchangers, as they were deemed to be a key component to match cabin temperature demand. It is of paramount importance to also study the interdependencies of the components within the system to understand the behavioural characteristics of fault occurrence and its propagation. This leads to identification of appropriate sensor installation locations to perform accurate diagnostics.

Based on the literature review, there is an evident gap in the open literature with regards to in-depth system-level analysis of the ECS. In the last four decades a handful of ECS simulation models have emerged in the literature, including: (i) Easy5 [8,9], (ii) FLECS [10,11], (iii) Flowmaster [12,13], (iv) Dymola [9,14] and (v) SESAC [15,16]. Among these models SESAC was purposefully developed by Cranfield University's IVHM Centre to support condition-based monitoring and diagnostics of civil aircraft ECS with the capability to introduce degradation in the simulation. It is interesting to note that these models have not been comprehensively verified using test data across each component, because there is very limited data coming from these legacy systems due to a lack of sensors.

To attain reliability on the model's capability to accurately estimate PACK performance under healthy and degraded scenarios, a systematic verification and validation (V&V) is necessary. As reported by Childs et al, an experimental rig was developed using a Hawk ECS to perform ECS model verification [17]. Similarly, an experimental investigation was conducted on a Boeing 737-200 aircraft to collect temperature, pressure and valve position to support verification

of an ECS thermodynamic model [18]. These two ECS cases are similar in terms of their architecture, and both have a low-pressure water separator system.

However, as reported in October 2020, there are only 60 Boeing 737-200 aircraft in service. This is significantly fewer than the 6393 next generations (NG) variant, the -600, -700, -800, and -900 [19]. Based on the sheer number of NGs still in service, and that the latest variant Boeing 737 MAX uses a pneumatic ECS with a high-pressure water separator (HPWS), there is a need for a 737 ECS Ground Test Facility (GTF) to be used for studying system performance in terms of temperature (T), pressure (P), mass flow ($\dot{m}$) and relative humidity (RH). Such a facility would also play a significant role in supporting future research on sensor optimisation and fault simulation analysis.

In the light of the aforementioned literature, there exist a gap in terms of the availability of experimental ECS data in order to support the development of a robust simulation framework for ECS fault diagnostics at system level. This chapter reports the development and qualification of a GTF for the in-situ experimental investigation of a B737-400 aircraft ECS. The data acquired through the successful testing of the developed GTF is used to conduct the V&V of the Cranfield University's in-house ECS simulation framework (SESAC) under a wide range of operating conditions. Figure 4-1 highlights the key steps deployed for the successful development and qualification of the B737 GTF and SESAC V&V and forms the core of this chapter. Firstly, some background on how the PACK operates and the SESAC simulation is given in Section 4.2.

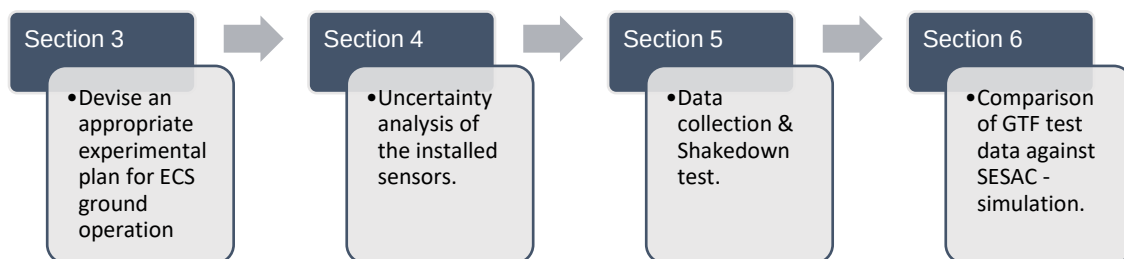


Figure 4-1 Employed steps for the GTF development, qualification and SESAC V&V.

4.2 Background - Overview of PACK Operation and SESAC

The ECS uses multiple subsystems (i.e. BAS, PACK and ADS) including a control system regulating flow across the system to meet temperature and pressure requirements in cockpit, cabin and avionics bay. The bleed system provides the pressurised air to the PACK for conditioning. Part of the bleed mass flow before entering the PACK is taken out to drive the Ram turbo-fan to drive cold ambient air over the heat exchangers in the PACK to enable pre-cooling of the bleed air. After conditioning of the bleed air in the PACK, the air is mixed with trim and recirculating air from the cabin in the mixing manifold before it is distributed in different zones of the aircraft.

The PACK is the primary system for conditioning the flow within the ECS, which makes it the focus of this study. Figure 4-2 shows a schematic of a single PACK in the B737-400. It consists of valves, heat exchangers, an air-cycle machine (ACM) and HPWS. Following the sequence shown in Figure 4-2, the PACK receives bleed air at high temperature and pressure, primary cooling takes place in the PHX, and secondary cooling takes place in the SHX, after the flow is compressed. Cold Ram air, which originates from outside the aircraft, flows through the Ram air duct and, after being used as a heat sink for PHX and SHX, is deposited back into the aircraft's airstream. After the SHX the temperature of the bleed air has been substantially reduced and the high pressure flow is expanded through a turbine, after passing through the HPWS to control humidity. At the outlet of the turbine the air temperature can potentially drop below freezing and, if this occurs, it is addressed by mixing in part of the bypass hot bleed flow through the TCV. The mixing of this air is controlled in order to match the PACK outlet temperature against the cabin demand.

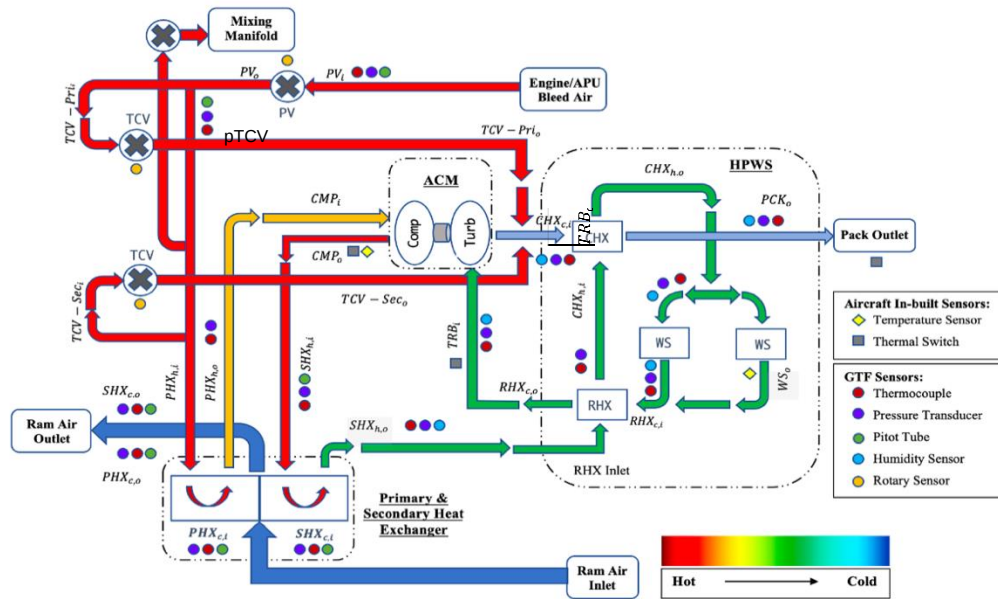


Figure 4-2 B737-400 PACK schematic with sensor installation locations

4.2.1 PACK Temperature Control

The cabin temperature demand can be regulated through the input dials mounted on the P5 overhead panel within the cockpit [20]. On the B737-400 aircraft, the cabin temperature demand can be regulated within the range of 18°C to 30°C. The PACK zone controller unit receives input from the P5 overhead panel, sensors listed in Table 4-24-3, and temperature sensors located inside the cabin, to meet target temperature in the cabin.

The PACK temperature control primarily acts in two ways: (i) by controlling the cold Ram air supply by regulating the Ram air inlet modulating flap, and (ii) by controlling the PACK outlet temperature through the hot bypass stream by regulating the TCV, see Figure 4-2. It is necessary to regulate the PHX, SHX and turbine outlet temperature to meet the lowest cabin demand (out of the three zones) using the temperature sensors listed in Table 4-24-3. These two inbuilt temperature sensors, at the CMP_o and WS_o , support the control system with necessary feedback to control the temperature throughout the PACK, and its compliance against the demanded cabin temperature.

Table 4-24-3 Inbuilt Temperature sensors for PACK temperature control

Temperature Sensor	Location	Threshold
Ram air temperature sensor	Compressor outlet duct (CMP _o)	Regulates Ram mass flow to maintain the Compressor outlet temperature to as near 110 °C as possible
PACK temperature sensor	Water extractor outlet duct (WS _o)	Regulates TCV opening to maintain the lowest temperature demand from the zone

4.2.2 Trim System

In addition to PACK temperature control, the P5 panel also provides control over the trim system main valve, which can be switched on and off. As illustrated in Figure 4-3, the function of the trim system is to ensure the supply of hot air to the cabin air distribution ducts, this allows the adjustment in the temperature supplied to each cabin compartment. For example, both forward and aft can be set to meet 24°C temperature demand, however, depending on the heat load of each compartment, the required temperature supply can vary in order to meet the demanded temperature. As shown in Figure 4-3, a small proportion of the mass flow going into the PACK core is used to fulfil the function of the trim valve. Switching on the trim system would therefore allow the PACK-zone controller to regulate (open or close) the trim valve based on the cabin temperature sensor feedback. The amount of mass flow going through the core of the PACK is therefore strongly dependant on the status of the trim valve, which can consequently affect the performance characteristics of the components mounted within the core of the PACK i.e. PHX, SHX, ACM, HPWS.

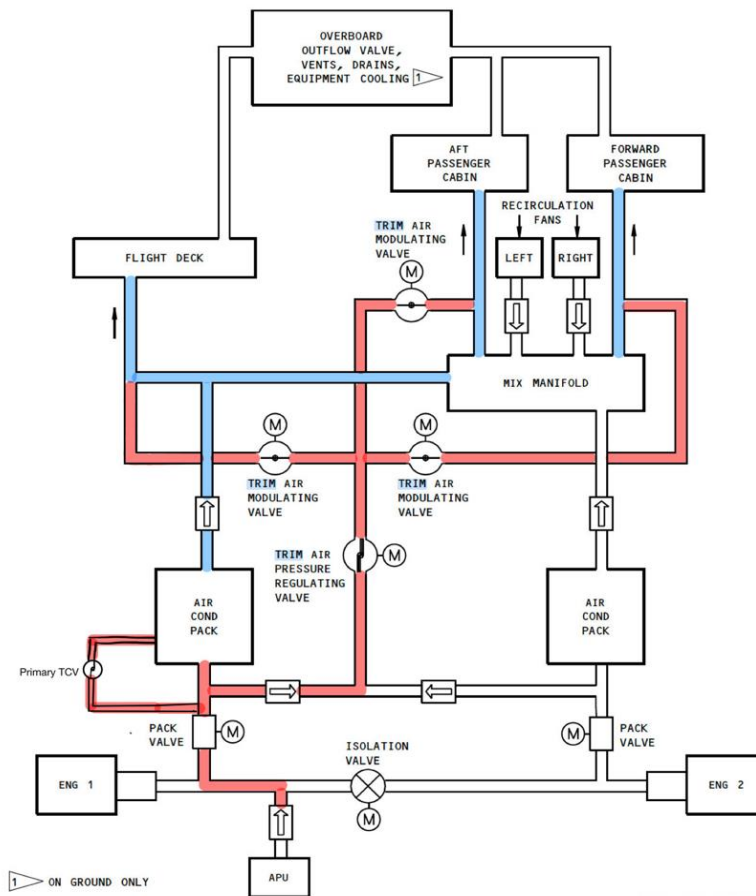


Figure 4-3 737- 400 ECS Schematic (red and blue annotation represent bleed air and conditioned air respectively), adopted and reproduced from Boeing 737-400 AMM [21]

4.2.3 ECS Simulation Framework – SESAC

SESAC is a MATLAB based ECS component library developed by Jennions et al. [15], enabling by a drag-and-drop interface. The authors have reported detailed analysis of PACK performance at cruise using data provided by Boeing. Figure 4-4 shows the SESAC PACK simulation model of a B737-800 developed at IVHM centre [15]. The model configuration of the B737-800 in terms of the architecture and flow sequence mirrors the B737-400 schematic presented in Figure 4-2.

The PACK receives input bleed air at high temperature and pressure from the engine (via the BAS), the quantity of which is controlled by the PACK valve (PV). The overall model is comprised of many different modules, and virtual

sensors for the control logic. Immediately downstream of the PV, the flow is split into two streams. Part of the air flow passes through the cold stream of the PACK, part of it is bypassed through the TCV and mixed at the TRB_o . In the cold stream, the flow proceeds through the heat exchangers, which use the Ram air as a heat sink to drop the temperature. The compressor, positioned between the heat exchangers, increases the air pressure in order to maximise the expansion through the turbine. The HPWS is composed of a reheater, condenser and water extractor, allowing the extraction of water content prior to the expansion of the air in the turbine.

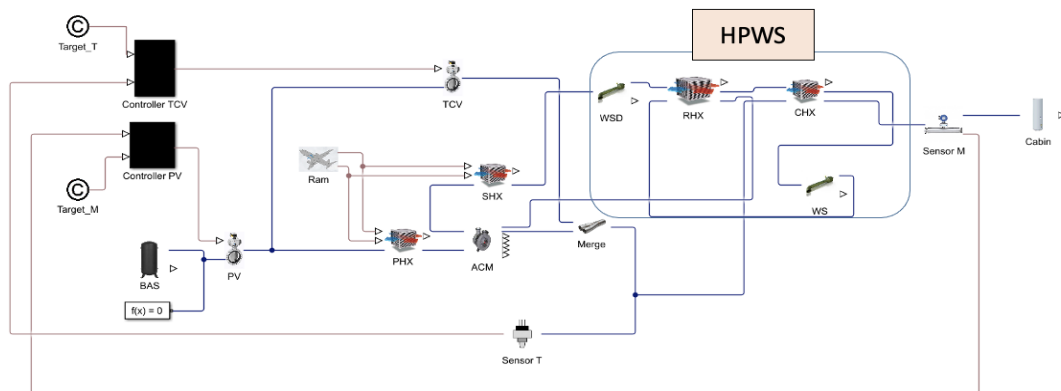


Figure 4-4 SESAC Simulation Model for B737-800 [15]

There are two control loops in the system, one for temperature and one for flow (Figure 4-4). A (virtual) temperature sensor placed at the outlet of the merge provides a feedback signal to the controller of the TCV, which regulates the TCV valve angle to deliver the required hot mass flow. Downstream of this is a (virtual) mass flow sensor, placed immediately downstream of the merge component providing a feedback signal to the PV mass flow controller, which regulates the overall mass flow.

4.3 Development of the B737-400 Ground Test Facility

Cranfield University owns a Boeing 737, which is used for education and research. The research emphasis is to turn the plane into a GTF for a number of aircraft systems. In the current work the emphasis is on the ECS, and the left-hand side PACK was selected for experimental work. In this section the selection

of sensors is summarised for completeness (previously reported by the authors [22]), along with the operational envelope of the experiments and the classification of data collection.

4.3.1 Sensor Selection and Installation

The PACK functionality is to condition the bleed air supplied by the Engines/APU which is generally at a very high temperature and pressure. Therefore, one of the key requirements for the sensor selection is to comply with the operating temperature and pressure at various locations.

Table 4-4 provides the list and the specifications of the selected sensors for measuring T, P, RH and valve angles. The maximum operating temperature of the pressure transducers (125°C) falls well below the expected temperature (approximately 180°C) at the PV_i , PV_o and $PHX_{h,i}$ stations [15]. Therefore, to protect the transducers from overheating at these stations, temperature isolation coils [23] were used. These coils are tube (0.635cm of diameter) made of stainless steel and specification suggests that a tube length of 7.62cm can drop the source temperature from 200°C to approximately 93°C through heat transfer into ambient air of temperature 38°C [24].

Table 4-4 List of sensors and their specifications defined by manufacturer

Manufacturing P/N	Type	Range	Temperature Range	Accuracy	Offset error	Total Error Band	Reference
Honeywell PX2EN1XX10 0PSAAX	Relative pressure	101.352 to 689 kPa	-40 to +125°C	±0.25% BFS L of FSS	±1% of FSS	±2% of FSS	[25]
Honeywell PX2EF1XX05 0PAAAX	Absolute pressure	0 to 344 kPa	-40 to +125°C	±0.25% BFS L of FSS	±1% of FSS	±2% of FSS	[25]
Omega, K-type Thermocouple K-L-1-6-40- G1/8-T-2	Temperature	0 to 400°C		±1.5°C	-	-	[26]
TE Connectivity HTM2500LF	Relative Humidity	0 to 100% RH	-40 to +85°C	±5%	-	-	[27]
Active Sensor MHR5210 CV- 090	Rotational angle	0 to 90°	0 to +150°C	±0.11%	-	-	Calibration test report provided by manufacturer

Monarch Engineering Services LTD conducted the disassembly of the left-side PACK, from which the PV, TCV, HXs, ACM and HPWS came out as a single unit. Appropriate safety measures were taken, such as pulling out circuit breakers, and covering and labelling ducts. The sensor bosses were manufactured in a laboratory and welded on the target site. Sensors were mostly installed on the ducts, and locations were selected based on the space available. The existing sensor boss available on the HPWS was utilised for humidity sensor installation by designing appropriate T-junctions and using compression fittings. The compression fittings were tested in the lab for suitability [22]. Sensor installation

plates were manufactured and welded on the HX inlet (Ram side) and Ram air outlet duct. The rotary sensors were installed on the PV, Primary TCV and Standby TCV. Removable rigs were designed and manufactured to connect the sensors with the pivotal point of the butterfly valves. After reassembling the PACK with all the sensors installed, the data acquisition unit (DAQ) was installed with all the sensors connected, as shown in Figure 4-5. An ethernet cable and a power supply cable were taken out from the bay, completing the hardware assembly of the B737 GTF.

The ECS was tested in a systematic approach for functionality. The APU was powered and allowed to reach steady-state (5 minutes time allowance). Electrical components were turned on to put a 100amp load on the APU. The ECS left-side PACK was then powered on for 5 minutes, after which ducts, and the replaced seals, were manually tested for leakages [22].



Figure 4-5 Ground test facility of the Boeing 737-400, Left-side PACK data collection

4.3.2 Definition of the Operational Envelope for Experimentation

The GTF is developed to conduct experimental testing of the PACK, with the aircraft on the ground, under various operating conditions and functional

scenarios. The scope of this chapter covers the experimental testing of the PACK under a wide range of operating conditions, i.e. hot and cold demand, trim on and off. The overall experimental tests were conducted over a number of different days with varying ambient conditions. The start-up sequence starts with powering up the APU. Once steady exhaust gas temperature is obtained from the APU, the bleed valve is energised from the P5 overhead panel in the cockpit. Subsequently, the left-side PACK is turned on and operated for 5 minutes, similar to the functionality test, then data collection begins in order to capture the steady-state operating data. Table 4-5 shows the operating conditions of the seven sets of data, labelled as reference cases (RCs), taken during the experimental program. These RCs account for data collected under different ambient and PACK operating scenarios and will be used in Sections 4.5 and 4.6 to support GTF qualification and V&V of SESAC respectively.

Table 4-5 Experimental test reference case classification

Reference Cases	Trim Status	Cabin Demand	Cabin Demand (°C)	$T_{amb}(^{\circ}\text{C})$
RC1	On	Hot	24	11.5
RC2	On	Hot	24	9.0
RC3	On	Hot	24	5.5
RC4	On	Cold	18	6.5
RC5	Off	Cold	18	6.5
RC6	On	Hot	24	5.5
RC7	Off	Hot	24	5.5

4.4 Uncertainty Analysis

In experimentation, every measurement is subjected to error as nothing is 100% perfect. Mathematically this phenomenon can be represented as:

$$\text{Measured Value} = \text{True Value} \pm \text{Total Error} \quad (4-1)$$

The total error can manifest itself in one of two ways: (i) Accuracy and (ii) Precision [28, p.36]. Accuracy error shows how far away the measured value is from the true value, and precision error represents the total spread of data in a given population. The following section presents the calibration tests conducted to quantify the errors associated with the sensors.

4.4.1 Accuracy

The accuracy error based on the worst-case scenario of the pressure transducers and thermocouple are given by the manufacturer as shown in

Table 4-4. To deduce the typical accuracy error associated with the sensor, laboratory tests were conducted on both the pressure transducers and thermocouples. The accuracy error is calculated as the difference between a known reading and measured data.

4.4.1.1 Pressure Transducers

The pressure acting on any surface is defined as the force acting per unit area of the surface. Based on this principle, pressure transducers are manufactured with a constant area diaphragm that undergoes deflection due to the force acting upon it. This deflection is measured and converted into an electrical output measured, in this experiment it's in volts [29]. Processing this electrical output provides an indication of the applied pressure. Inevitably the sensor readings are subject to offset, pressure non-linearity, hysteresis, non-repeatability, thermal effect on offset and thermal hysteresis errors [25].

The offset error refers to the start of the measuring range and can be higher or lower than actual [30]. The contributing factors in causing this error are pressure change frequency and amplitude, temperature fluctuations, material responses and environmental changes [31]. Before starting the APU and ECS all transducers should measure atmospheric pressure, any deviation from this being the offset. This offset, for all the pressure transducer locations, over a five day period, is shown in Table 4. It can be seen that the offset on each day varies across the transducers, and across the days, the maximum offset observed being 5.77 kPa. As per the specification provided by the manufacturer (Table 2), the maximum offset quoted for the relative pressure, at 25°C, was 6.89 kPa. The measured offset, as shown in Table 4, is recorded and used on each experimental data collection following the procedure suggested by the manufacturer [32].

Table 4-6 Offset error variation across each pressure transducer (kPa)

	PV_i	pTCV	$PHX_{h,o}$	CMP_o	$RHX_{h,o}$	$CHX_{h,o}$	WS_o	$RHX_{c,o}$	$Merge_o$	PCK_o
Day 1	2.35	1.64	3.63	4.4	5.42	3.69	4.14	1.29	3.91	2.31
Day 2	1.45	0.71	2064	3.59	4.51	2.83	3.31	0.26	3.06	1.39
Day 3	0.52	-0.84	1.19	1.25	1.67	1.59	1.05	1.49	0.19	0.49
Day 4	1.33	-0.69	-0.49	1.36	0.47	2.29	1.40	-0.13	1.38	1.31
Day 5	1.89	1.75	3.23	5.58	5.77	3.6	3.72	1.06	2.32	2.29

Referring to

Table 4-4, the manufacturer has given the accuracy of the absolute and relative pressure transducers to be about 0.86kPa (0.25% of 345kPa) and 1.72kPa (0.25% of 689kPa) respectively, which includes pressure hysteresis, non-linearity, and non-repeatability errors. The pressure hysteresis, non-linearity and repeatability corresponds to the maximum deviation of the sensor reading from the actual value, total error in Eq. 4-1.

To investigate accuracy further, a reference pressure kit [31] was used to apply a known pressure to the pressure transducer at room temperature of 20°C. The sensor data was recorded using the same data acquisition unit as on the aircraft. Figure 4-6 shows the load condition (LC) on the x-axis, applied pressure and measured pressure on the primary y-axis, and the difference between applied and measured pressure on the secondary y-axis. A maximum difference of approximately 0.58kPa and 0.6kPa pressure was observed in this test for both the absolute (50 psi) and relative (100 psi) pressure transducer respectively.

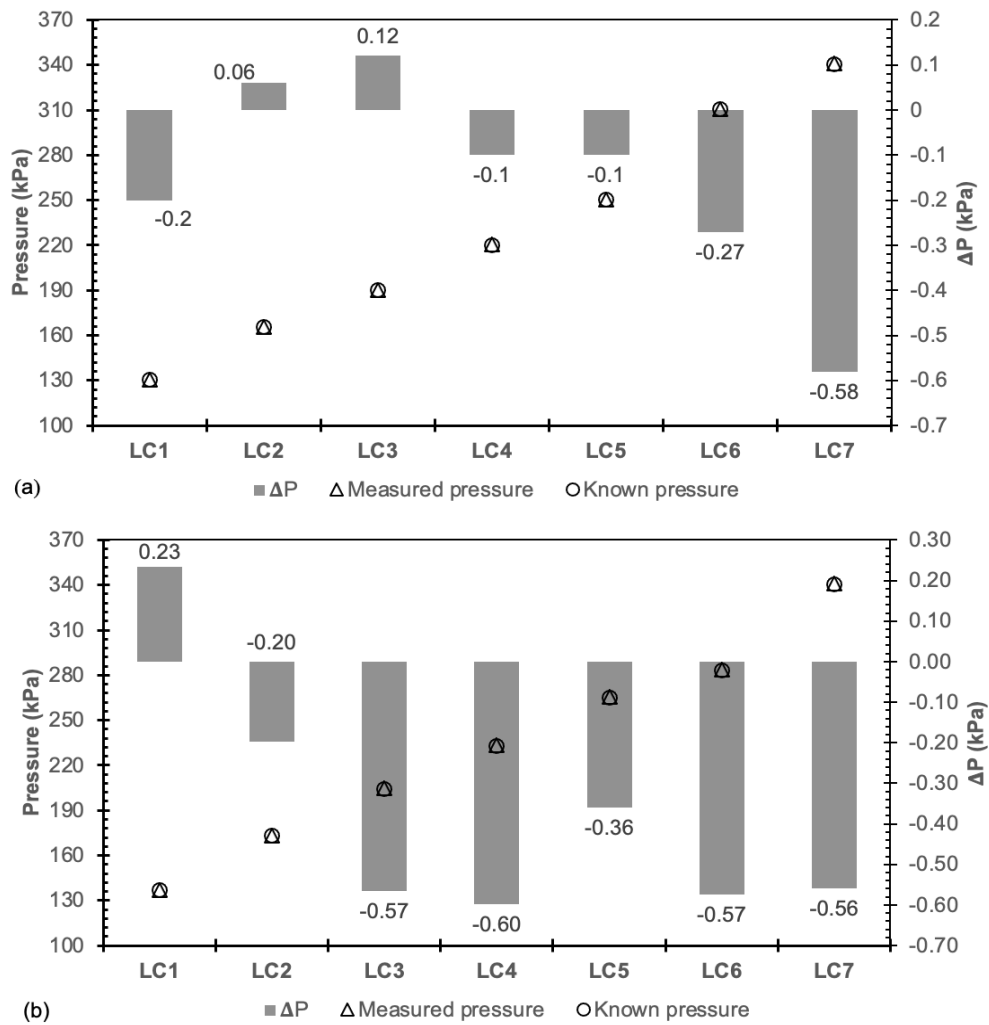


Figure 4-6 (a) Absolute pressure transducer and (b) relative pressure transducer error in pressure reading recorded under ambient temperature of 20°C.

In addition to conducting tests under room temperature, oven tests were conducted on the relative pressure transducer as they are installed at the high temperature stations across the PACK. As highlighted in section 4.3.1, due to the use of temperature isolation coil the temperature of the source is dropped to approximately 100°C, therefore, the transducer was tested under 53°C (midpoint) and 100°C (maximum expected temperature at the transducer). Table 4-7 shows the tests result highlighting the applied load (true pressure), pressure readings (measured pressure) and the maximum ΔP between the true and measured value. The maximum ΔP , which can be attributed to the pressure non-linearity, hysteresis, and non-repeatability, is observed to be around -0.6kPa.

Table 4-7 Thermal control chamber pressure (kPa) test result with increased load at 53°C and 100°C operating temperatures

	53°C			100°C		
	True Pressure	Measured Pressure	ΔP	True Pressure	Measured Pressure	ΔP
Test 1	212.10	212.70	-0.6	212.10	211.97	0.13
Test 2	234.10	234.36	-0.26	234.10	234.56	-0.46
Test 3	289.10	288.90	0.20	289.10	288.84	0.26
Test 4	304.10	303.51	0.59	304.10	303.55	0.55

From the test results it has been deduced that the pressure transducers are far more accurate in comparison to the maximum accuracy specified by the manufacturer. The uncertainty (maximum error observed) for the absolute and relative pressure transducer is deduced to be $\pm 0.58\text{kPa}$ and $\pm 0.6\text{kPa}$. The absolute pressure transducers are installed at the $\text{CHX}_{h,o}$, $\text{RHX}_{c,o}$, Merge_o , PCK_o and Ram inlet-outlet and relative pressure transducers are installed across the rest of the stations across the PACK. As the uncertainty for both the transducers are seen to be almost identical, therefore $\pm 0.6\text{kPa}$ of accuracy error will be used in rest of the chapter.

4.4.1.2 Thermocouples

With the K-type thermocouple used here the technical specification suggests the accuracy to be within $\pm 1.5^\circ\text{C}$ [26]. In order to verify the accuracy of the thermocouple, an ice and boiling water test was conducted. Data was collected for 1 minute at 10Hz while the thermocouple was dipped in ice and then boiling water. It was noticed that the total accuracy error in measuring the temperature of ice and boiling water was 0.14% and 0.04% respectively. The maximum difference between expected and thermocouple measurement is found to be -0.38K. This indicates that the thermocouples used in the experimentation are significantly more accurate than the pressure transducers.

4.4.2 Precision

The precision error of the sensor readings highlights the spread of a data sample. This error can occur due to unknown and unpredictable changes in the experiment or the environment, and it is unbiased and cannot be eliminated. Calculating the mean (μ) of the data collected at a steady state is used in experimentation to account for such unbiased error. Peters, C [33], mentioned in a book chapter that this error typically falls within one standard deviation or Std.Dev (σ) with a 68% confidence interval. This is true if the data set is normally distributed at which case mean, median and mode are equal [34, p.101].

To verify if the data sample is distributed normally, a histogram plot for different sample sizes was plotted, and is shown in Figure 4-7. Measured values are shown in blue, over three data collection times (30s, 1min, 2mins), and the best fit normal distribution from SPSS is shown as the bell curve. Overall there is only a very small change in pressure statistics across the three measuring times with the thermocouple readings showing more of a change (but again very small).

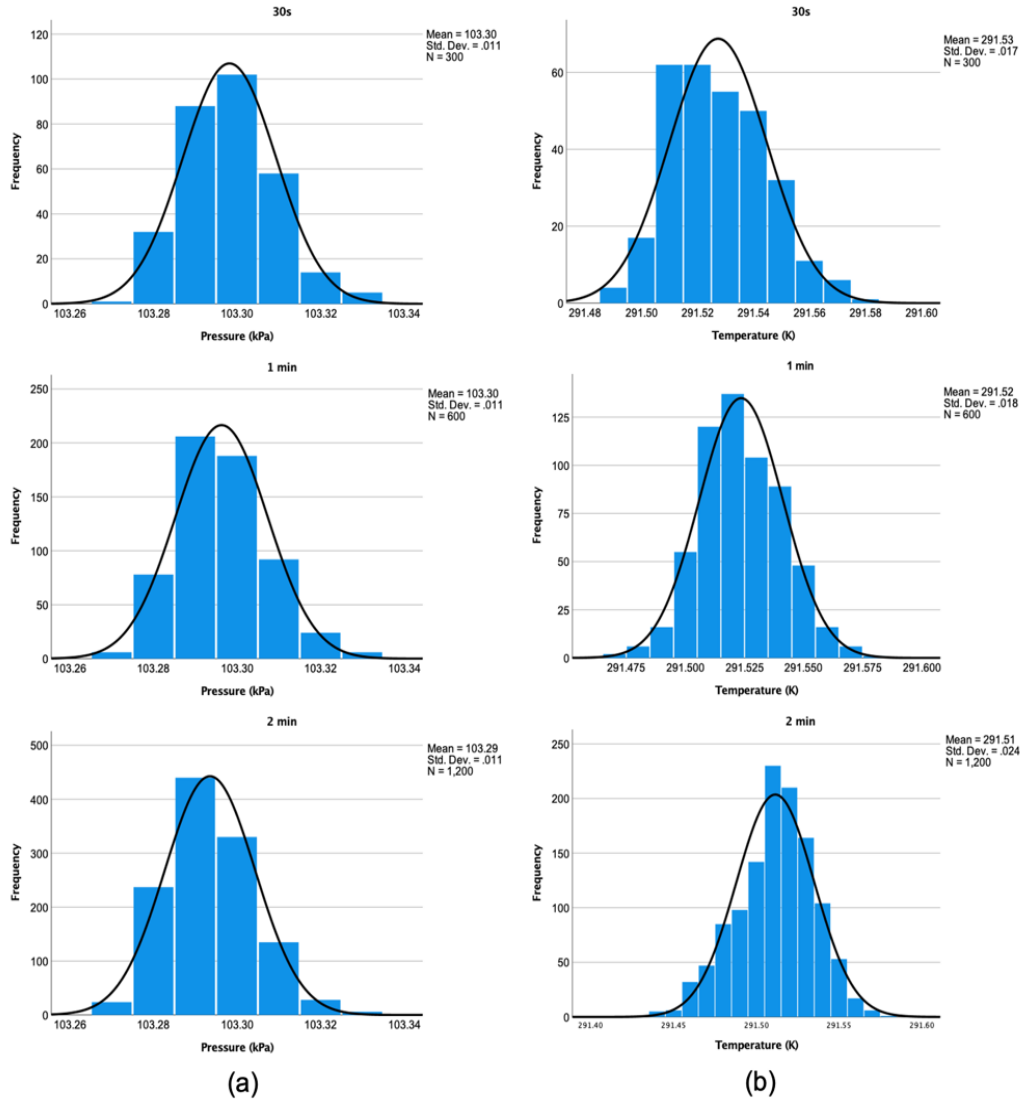


Figure 4-7 Histogram plots: (a) Pressure transducer and (b) Thermocouple

To verify normality of the data, the calculated mean, median and skewness value of the data samples are used, see Table 4-8. The skewness value is used to quantify the asymmetric nature of the distribution and is 0 for standard normal distribution [35]. Mishra et al. suggested that skewness value between +1 and -1 can be used as an indicator for the normality of the data [36]. As shown in Table 4-8, the skewness value for both T and P is found to be within +0.39 and -0.3. It is also noted that the mean and median are approximately the same for all cases, corroborating normality of the data. Furthermore, it has been observed that the mean value and the standard deviation do not significantly change with increased sample size. Thus, 600 samples for estimation are chosen for data analysis in

this experimentation and the precision error of the pressure transducers and thermocouples are calculated to be 0.01kPa and 0.02K respectively.

Table 4-8 Statistical data of pressure transducer and thermocouple

Pressure			
	30 second	1 minute	2 minutes
Sample size	300	600	1200
Mean, μ (kPa)	103.30	103.30	103.29
Median (kPa)	103.30	103.30	103.29
Std. Deviation, σ (kPa)	0.01	0.01	0.01
Skewness	0.33	0.37	0.39

Temperature			
	30 second	1 minute	2 minutes
Sample size	300	600	1200
Mean, μ (kPa)	291.53	291.52	291.51
Median (kPa)	291.53	291.52	291.51
Std. Deviation, σ (kPa)	0.02	0.02	0.02
Skewness	0.35	0.13	-0.30

Based on the above experiments, the root mean square error (RMSE) is calculated for each sensor:

$$\text{RMSE} = \pm \sqrt{(\text{Accuracy error})^2 + (\text{Precision error})^2} \quad (4-2)$$

As the sensors are proven to be precise, the errors are seen to be dominated by the effect of the accuracy of the sensors. Thus, the total uncertainty error, using Eq. 4-2, is deduced to be:

$$\text{Measured pressure reading} = \text{True Value} \pm 0.6 \text{ kPa} \quad (4-3)$$

$$\text{Measured temperature reading} = \text{True Value} \pm 0.38 \text{ K} \quad (4-4)$$

4.4.3 Error Propagation to Mass Flow

Figure 4-8 shows the instrumentation for flow measurement. Mass flow was calculated as a product of the density (ρ), area (A) and velocity (v):

$$\dot{m} = \rho A v \quad (4-5)$$

A pressure transducer was installed on the duct wall and a thermocouple inserted into the duct was used to measure the static pressure (P_s) and temperature (T) of the flow. These measurements were used to calculate the density:

$$\rho = \frac{P_s}{RT} \quad (4-6)$$

where R is the universal gas constant, 287.05 JK/kg.

The velocity of the flow could not be measured directly. Thus, a total pressure probe was manufactured and installed facing the direction of the flow; the pressure transducer was mounted at the tip to measure the total pressure (P_t) of the flow. The measured P_t and P_s was used to calculate the dynamic pressure (P_d):

$$P_d = P_t - P_s \quad (4-7)$$

Subsequently the velocity was calculated as a function of P_d and ρ :

$$v = \sqrt{\frac{2P_d}{\rho}} \quad (4-8)$$

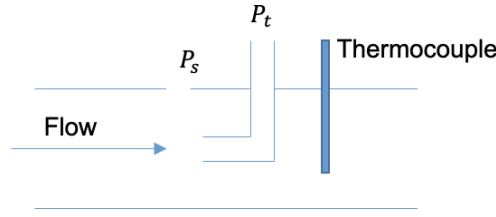


Figure 4-8: Instrumentation for mass flow measurement

The steps for mass flow error calculation are adopted based on the method described in [37]. The maximum accuracy error observed in testing of pressure transducer ($\pm 0.6\text{kPa}$) and thermocouple ($\pm 0.38\text{K}$) are used to calculate the maximum error propagation to mass flow. First, the error propagation to P_d from the P_t and P_s measurements is calculated.

$$\delta P_d = \sqrt{\delta P_t^2 + \delta P_s^2} \quad (4-9)$$

Similarly, the error propagation to density ρ is calculated as,

$$\delta \rho = \rho \sqrt{\left(\frac{\delta P_s}{P_s}\right)^2 + \left(\frac{\delta T}{T}\right)^2} \quad (4-10)$$

Subsequently the error propagation to velocity is calculated using,

$$\delta v = v \sqrt{\left(\frac{\delta P_d}{P_d}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2} \quad (4-11)$$

Finally, the error propagation to mass flow is calculated:

$$\delta \dot{m} = \dot{m} \sqrt{\left(\frac{\delta \rho}{\rho}\right)^2 + \left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta A}{A}\right)^2} \quad (4-12)$$

Using the above-mentioned equations, the error propagation to mass flow for the experimental data is reported in Sections 4.5 and 4.6.

4.5 GTF Experimental Validation

In this section the validity of the T , P and $\dot{m}$ data collected from the GTF is presented. To do this, the first step is to conduct a sensor continuity check which

helps to identify the installed sensor locations throughout the PACK that successfully generate data. Subsequently, the measurements acquired in terms of T and P under various ambient conditions are presented and discussed based on first principles and best engineering knowledge of the PACK operation. This is done with the aim of verifying the repeatability of the GTF for producing the PACK T and P data. Following that, based on the acquired T and P (static and total) measurements, the derived mass flow values at various locations of the PACK are discussed. Finally, the overall acquired data in terms of the T, P and $\dot{m}$, under various PACK operating modes including the effect of the trim system, is presented and discussed in order to verify the consistency of the data generation.

4.5.1 Sensor Continuity Check

Table 4-9 provides an overview of the installed sensor locations throughout the PACK. These locations are consistent with the stations illustrated in Figure 4-2. The table shows the working status of the installed sensors for data collection. Since the scope of this chapter is limited to verification of SESAC in terms of T , P and $\dot{m}$, the discussion on the RH and valve angle sensors is omitted, and only the sensors related to the measurements of T , P and $\dot{m}$ are discussed. The sensor continuity checks were first performed under ambient conditions, while keeping the PACK switched off, and were found to be successfully generating data. However, upon running the PACK, it was discovered that the PT1, PT4, PT5, PT6 and PT7 sensors as illustrated in

Table 4-9 were providing misleading data. At PT1 the total pressure probe was broken when fitting the PACK into the aircraft and could not be replaced due to limited access. With regards to PT4, PT5, PT6 and PT7 sensors, these represent Ram total pressure sensors, and they failed to provide usable data due to the positioning of their respective pitot-static tubes within the Ram duct. Therefore, the data acquired from these sensors was excluded from the analysis. Since the data measurements failed at these locations, alternative engineering based approaches were devised in order to determine the mass flow at target locations, and are outlined in Section 4.5.3.

Table 4-9 Sensor working status

Sensor Location	Temperature	Static Pressure	Humidity	Valve Angle	Total Pressure
Core					
PV _i	T1	P1			Pt1
pTCV	T2	P2			Pt2
PHX _{h,o}	T3	P3			
CMP _o	T4	P4			Pt3
SHX _{h,o}	T5		RH1		
RHX _{h,o}	T6	P6			
CHX _{h,o}	T7	P7	RH2		
RHX _{c,i}	T8	P8	RH3		
RHX _{c,o}	T9	P9	RH4		
TRB _o					
CHX _{c,i}	T10	P10	RH5		
PACK _o	T11	P11	RH6		
Cold Side (RAM)					
PHX _{c,i}	T12	P12			Pt4
PHX _{c,o}	T13	P13			Pt5
SHX _{c,i}	T14	P14			Pt6
SHX _{c,o}	T15	P15			Pt7
Valve					
PV				V1	
TCV-Pri				V2	
TCV-Sec				V3	

Legend	
	Successfully acquired data
	Broken
	Unable to generate usable data
	Out of scope of this paper

4.5.2 Temperature and Pressure Measurements

Having successfully completed the continuity checks on the sensors, the next step is to generate T and P data throughout the PACK under different ambient conditions while operating the PACK under constant cabin demand. This process will provide data that can be used to assess the repeatability of T and P data acquisition using the GTF. Reference cases RC1, RC2 and RC3 were selected from Table 3 as they all represent cabin demand of 24°C with the trim system on, under varying ambient condition.

Figure 4-9 (a) and (b) present the acquired T and P data for the selected RCs. Note that as determined in Section 4.4.2, the measured T and P values have an uncertainty of $\pm 0.38\text{K}$ and $\pm 0.6\text{ kPa}$ respectively. The error bars could not be incorporated in Figure 4-9 due to the relatively small variation in uncertainty relative to the scale of the measurement. Referring to Figure 4-9(b), the station pTCV represents the PV outlet condition, where a pressure drop is apparent with respect to the station PV inlet (PV_i). This pressure drop across the PV occurs due to the pressure losses associated with the installed butterfly valve. In Figure 4-9(a), a small temperature drop of approximately 4K is also noticed across the PV, which can be attributed to heat loss to the ambient air.

Analysing both T and P downstream of the pTCV location, the flow travels through the core section of the PACK (see Figure 4-2). Immediately downstream of the pTCV is the PHX, which uses the Ram air as a heat sink to significantly drop the temperature of the bleed air. As shown in Figure 4-9(b), a small pressure drop across the PHX is observed which is due to the inherent pressure losses associated with the PHX. After the PHX the air undergoes compression in the ACM compressor which increases both the temperature and pressure of the air as seen at location CMP_o in Figure 4-9. Post compression, a temperature drop at the $SHX_{h,o}$ is observed in which the SHX removes most of the heat added due to compression. Beyond this stage, humidity is removed from the air in the HPWS, which is composed of a series of heat exchangers acting as a reheater and a condenser. As expected, as the air passes through these heat exchangers, the temperature varies marginally to allow condensation and water extraction and the pressure drop occurs due to the inherent pressure losses associated with the heat exchangers. Once the air has humidity removed, it is supplied to the turbine for expansion.

Due to the turbine expansion, both the pressure and the temperature of the air drop substantially. In Figure 4-9(b), the effect of the pressure drop due to expansion across the turbine can be seen at the $Merge_o$ location. The turbine outlet temperature can often reach below freezing, which wasn't captured in the data as it was not possible to install a thermocouple directly after the turbine outlet due to space limitation. At this point, the hot bleed flow from the TCV-Pri is mixed at the merge component placed immediately downstream of the turbine in order to prevent ice formation and match the demanded temperature. The aircraft utilises a factory-installed thermal sensor at WS_o , which dictates the opening and closing of the TCV in order to match the demanded temperature. This broadly explains the behaviour of the T and P across each component as the bleed air goes through the PACK.

The overall variation observed in the RCs presented in Figure 4-9 can be attributed to multiple factors such as:

- i. The APU provides the bleed air which according to the maintenance manual [21] vary with respect to the ambient condition.
- ii. As the experiments were performed on different days, the cabin temperature across different cabin zones cannot be practically maintained at a constant temperature. This affects the temperature control loop of the PACK-zone controller, which consequently has an impact on how the flow control valves such as the TCV and trim are regulated in order to deliver the demanded cabin temperature.
- iii. The variation in pressure across the ACM (CMP_o through to $RHX_{c,o}$) can be attributed to the differences in the mass flow through the core, regulated by the PACK zone controller through the trim system mass flow extraction.
- iv. The variation observed in the temperature profile, see Figure 4-9(a), are found to prominent across the HPWS (from $SHX_{h,o}$ through to $RHX_{c,o}$). As the function of the HPWS is to regulate humidity and extract excess water content from the air, the variation in temperature can be sensitive to the RH in the bleed air on the test day [15].
- v. At the WS_o station the temperature should match the demanded temperature according to the AMM, this is not found to be the true in all cases. The exact reason why the PACK is not able to match the demanded temperature at WS_o cannot be pointed out due to the inherent highly integrated nature of the PACK with the upstream bleed and the downstream air distribution and trim system, as well as the intervention of the PACK zone controller on the overall system.

Considering the aforementioned limitation associated with the experimental testing on an actual aircraft, it can be safely said that the developed GTF is capable of producing data for temperature and pressure which is found to be repeatable in terms of the trend. This is in the sense that the acquired data is coherent in terms of representing the physics of the PACK components. The acquired data shown in Figure 4-9 is logical in terms of capturing the components functional outputs, and that it follows the physics first principles of the system. However, the engineering aspect of the data cannot be repeatedly reproduced

due to the limitation associated with the lack of knowledge and control over the other sub-system i.e., bleed air, air distribution, trim system, and the PACK control system. For example, without any insight of the employed PACK zone control logic, it is not possible to reason why the WS_o temperature can't be matched against the demanded temperature. Furthermore, the RC2 pressure rise across the compressor is significantly lower relative to the RC1 and RC3, this is due to the fact that for RC2 the trim system extracts higher mass flow, resulting in reduction in the core mass flow which consequently affects the operating point of the ACM for RC2. Without any detailed insights of the control logic employed for the control of the trim system the engineering reason for why the trim system decided to extract more mass flow for RC2 relative to RC1 and RC3 cannot be systematically comprehended.

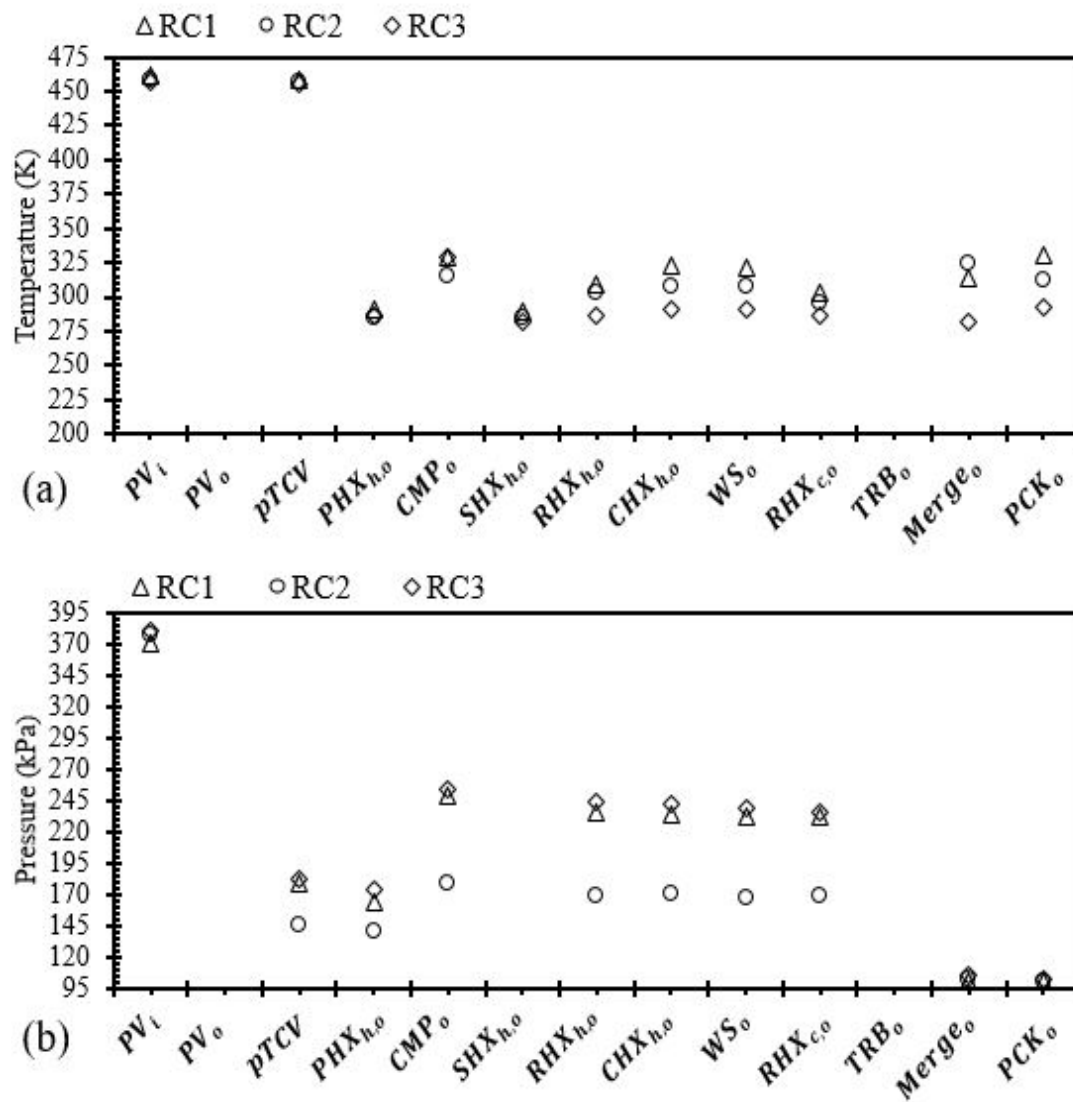


Figure 4-9 GTF repeatability test data, (a) Temperature, (b) Pressure.

4.5.3 Mass Flow Measurements

Mass flow measurements were attempted at four locations throughout the PACK: (i) PV_i , (ii) $pTCV$, (iii) CMP_o , and (iv) Ram. Out of the four, successful measurements were attained at only two locations: (i) $pTCV$ and (ii) CMP_o .

With regards to the Ram mass flow, the total pressure transducers installed at the PHX and SHX Ram inlet generated unusable data, and instead, the measured temperature readings across the PHX and SHX, and the measured CMP_o mass flow values were used to determine the Ram mass flow. This was

based on an energy balance matching the heat picked up by the Ram flow against the heat absorbed by the flow through the heat exchanger:

$$\dot{m}_{\text{Ram}} = \frac{\dot{m}_{\text{CMP},o} * c_p * (T_{\text{PHX},ho} - T_{\text{PHX},hi})}{c_p * (T_{\text{PHX},ci} - T_{\text{PHX},co})} \quad (4-13)$$

The pitot-tube intended to measure PV_i was found to be broken, when the PACK was installed back into the aircraft, and an alternative approach was taken to determine the PACK inlet mass flow. Upon switching on the PACK under a given cabin temperature demand, the PV opens, and flow enters the system. As stated in Section 4.2.1, there exists a control loop that regulates the opening of the TCV-Pri valve based on the WS_o temperature sensor feedback. At the beginning of the PACK start-up sequence, the WS_o temperature sensor will not immediately see a rise in temperature, and hence the PACK controller (due to lag) will not respond. Therefore, the TCV remains spring loaded closed and will only open once the initial control loop between the PACK controller and the WS_o sensor is completed [20].

Figure 4-10(a) illustrates a simplified view of the station sequence from PV_i through to CMP_o , and highlights the location of the pressure transducers and thermocouples installed for supporting the mass flow measurement. A mass flow reading is taken at the pTCV location immediately downstream of the TCV_pri bypass, and at CMP_o . Therefore, engineering judgement would suggest that, for PACK operating conditions under which the TCV_pri bypass valve is closed (e.g. during initial phase of the PACK start-up), the mass flow measured at pTCV would represent the mass flow through the PV. This is because the PV regulates a near constant mass flow for any given ambient condition [21].

As shown in Figure 4-10(b), when the PACK is switched on, the measured pTCV mass flow peaks and then gradually reduces. From the preceding discussion, the peak is due to the TCV-Pri being closed and all the bleed mass flow fed through the pTCV station. Once the WS_o sensor completes the initial feedback loop with the PACK controller, the TCV-Pri opens and part of the mass flow is fed through the TCV stream, accounting for the drop in pTCV mass flow and the approach to steady state, around 10 seconds after the start. The mass

flow characteristics presented in Figure 4-10 are found to be consistent for all the RCs presented in Table 4-5.

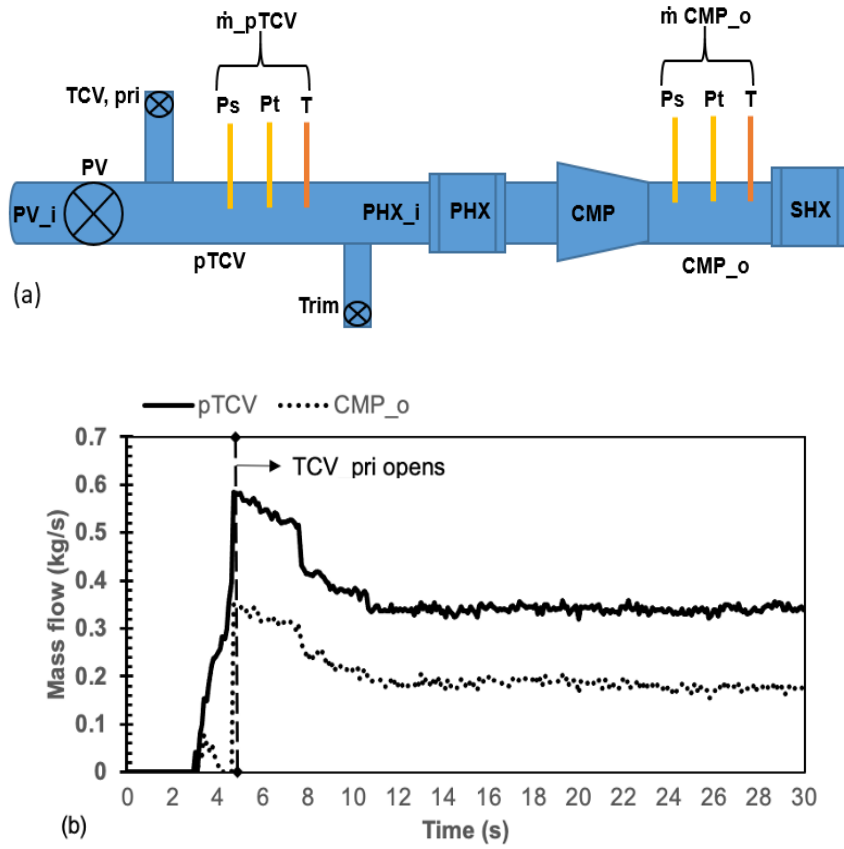


Figure 4-10: (a) Simplified schematic for mass flow measurements, (b) Measured mass flow as a function of test time at pTCV and CMP_o stations, 0 = PACK off.

Based on the above engineering judgement it was assumed that the mass flow peak observed at pTCV provides a good estimation of the mass flow at PV_i. The measured initial peak mass flow values at pTCV, as well as the corresponding steady state values for pTCV, and CMP_o, for RC1, RC2 and RC3, are presented in Table 4-10. Also presented are the derived Ram mass flow values based on the energy balance equation (Eq. 4-13). The TCV-Pri mass flow is derived using:

$$\dot{m}_{\text{TCV-Pri}} = \dot{m}_{\text{initial peak at pTCV}} - \dot{m}_{\text{pTCV}} \quad (4-14)$$

In Figure 4-10(b), it is seen that the measured CMP_o mass flow reaches a peak and then gradually drops due to the opening of the trim valve before

reaching a steady state. As the trim valve is placed between the pTCV and CMP_o location, the trim mass flow is derived as the difference between these two measured mass flows:

$$\dot{m}_{\text{Trim}} = \dot{m}_{\text{pTCV}} - \dot{m}_{\text{CMP}_o} \quad (4-15)$$

Note that all three cases presented in Table 4-10. were tested on three different days under same PACK demand of 24C. The ambient conditions are 11.5°C, 9°C and 5.5°C respectively for RC1, RC2 and RC3. Starting from the initial peak measured at the pTCV which represents the bleed flow through the PV ($\dot{m}_{\text{PV}_i}$ mass flow), it can be seen that the PV inlet mass flow increases with increase in ambient temperature, this is found to be consistent with the performance characteristics of the APU prescribed in the AMM [21]. With regards to the Ram mass flow, as per the AMM [21], during ground operations the Ram door is fully open in order to allow maximum mass flow to flow through the PHX and SHX. The acquired Ram mass flow values remain consistent across all three cases.

The TCV and trim mass flows are regulated by the PACK zone controller based on the thermal sensors installed at the PACK, mixing manifold and cabin. The data suggests that relative to the inlet mass flow the controller extracts 24%, 50%, and 30% of the mass flow and bypasses it through the trim system for RC1, RC2, and RC3 respectively. The controller characteristics for RC1 and RC3 concur reasonably, however, the extraction of as much as 50% of inlet mass flow for RC2 is peculiar specifically when considering the fact that in all three cases the PACK demand is maintained constant. Such behaviour of the control system cannot be explained without detailed knowledge of the employed control logic. The acquired pressure data, as shown in Figure 4-9 for all three RCs is consistent with the mass flow data shown in Table 4-10. RC1 with highest mass flow through the core corresponds to higher pressure rise across the compressor and likewise for RC2 with lowest mass flow through the core corresponds to lowest pressure rise across the compressor. It is clear that both the TCV and trim mass flow have a direct impact on the mass flow through the core of the PACK and therefore on the performance characteristics of the core components i.e. PHX, SHX, ACM,

HPWS. It can therefore be safely claimed that the developed GTF supports the acquisition of T, P and $\dot{m}$ data that obeys the physics first principles of the PACK system components operating under different ambient conditions. The engineering aspect of the PACK i.e. the controller characteristics cannot be adequately reproduced due to lack of access to the employed control logic and the characteristics of the downstream systems i.e. mixing manifold, air distribution, trim system.

Table 4-10 Measured and derived mass flows (kg/s) for RC1, RC2 and RC3.

Reference cases	Initial peak measured at pTCV	TCV-Pri (derived)	pTCV (measured)	Trim (derived)	CMP _o (measured)	Ram (derived)
RC1	0.680	0.175	0.505	0.163	0.342	0.693
RC2	0.615	0.062	0.553	0.321	0.232	0.691
RC3	0.585	0.065	0.520	0.180	0.340	0.695

4.5.4 Consistency Test

Having demonstrated that the GTF can generate T, P and $\dot{m}$ data throughout the PACK under different ambient conditions, the next step is to analyse the GTF's capability to capture the PACK performance characteristics under different operating modes, i.e. hot and cold cabin demand with trim system on and off, as given in Section 4.3.2 To do this, the RCs selected for the demonstration of this activity are: (i) RC3 (hot demand–trim on), (ii) RC4 (cold demand-trim on), (iii) RC5 (cold demand-trim off), and (iv) RC7 (hot demand-trim off). Note that hot and cold refer to cabin temperature demands of 24°C and 18°C respectively (Table 4-5). Figure 4-11 and

Table 4-11 represent the acquired T, P and $\dot{m}$ data for the selected RCs. The overall analysis of the acquired data is presented in two parts, first the corroboration for the PACK hot and cold operation with trim system off (RC5 and RC7) is presented, and then the discussion with regards to (RC3 and RC4) the effect of trim system being on and off under hot and cold demand is given.

In terms of the PACK hot and cold demand with trim off operation, it is expected that under the cold demand operation, the ACM must be operated as such that it provides maximum expansion in order to attain maximum cooling through the turbine. For a given cold demand operating condition this can be accomplished by minimising the bypass flow through the TCV and trim, and allowing maximum mass flow to flow through the core of the PACK in order to maximise turbine expansion. Likewise, under the hot demand operating condition, it would be favourable to minimise the expansion through the turbine by allowing minimum mass flow to flow through core.

The acquired results for mass flow under cold demand and hot demand with trim system off are presented in

Table 4-11. First, as the RC5 and RC7 cases corresponds to the trim off condition there is no flow expected to flow through the trim valve. As shown in

Table 4-11, the trim mass flow value for RC5 is 0.044kg/s and for RC7 is 0.01kg/s, derived using Eq. 4-15. The respective values for the trim flow are attributed due to the presence of uncertainty associated with the measured T and P values and its propagation to mass flow measurements at pTCV and CMP_o as explained in Section 4.4.3. The corresponding uncertainty values for pTCV and CMP_o mass flows are tabulated in

Table 4-11, and the resultant uncertainty propagated to the trim mass flow is calculated using:

$$\delta\dot{m}_{\text{Trim}} = \sqrt{\delta\dot{m}_{\text{pTCV}}^2 + \delta\dot{m}_{\text{CMP}_o}^2} \quad (4-16)$$

This gives trim mass flow uncertainty values of ± 0.117 and ± 0.122 kg/s for RC5 and RC7 respectively. These uncertainty values clearly bound the trim flows given in Table 9 and explain their near zero values in terms of experimental uncertainty.

With regards to the TCV flow, it would be expected that the PACK controller must bypass lower mass flow through the TCV for RC5 relative to RC7. RC5 have a 19% lower mass flow through the TCV and with trim system off, this leads to 28% higher mass flow through the core for RC5 relative to RC7. With higher mass flow through the core, a higher expansion through the turbine is attained, which translates to more power being transferred to the compressor relative to the RC7. As a result, both the T and P at the compressor outlet are found to be higher relative to the hot demand cases, shown in Figure 4-11(a) and (b).

Note that at the stations $\text{PHX}_{h,o}$ and $\text{SHX}_{h,o}$ of Figure 4-11(a), the temperature drop is marginally less in the cold temperature demand cases. The cold Ram mass flow through the PHX and SHX remains constant throughout all four cases. However, the increase in the core mass flow (i.e. hot mass flow for PHX) has an effect on the heat transfer through the PHX and SHX, following Eq. 4-13. Downstream of the SHX, humidity is removed from the air in the HPWS components. Discussion of humidity is not within the scope of this work and so will be omitted.

As discussed in Section 4.2.2, if the trim system is switched on then the PACK-zone controller dictates the status of the trim valve based on the cabin temperature feedback and the imposed cabin demand. This has a consequent

impact on the amount of mass flow that can be attained through the PACK core. RC4 presents cold cabin demand with trim system on, however, despite of trim system being on, no flow through the trim system is observed. The trim mass flow value for RC4 is derived to be 0.035kg/s and is within the uncertainty error. The likely reason why the PACK-zone controller decided to close the trim valve is to allow maximum mass flow to flow through the core in order to maximise expansion through the turbine as desired in order to adhere with the cold demand. Therefore, the observed PACK performance characteristics for RC4 coincide closely with RC5 under which the trim system is kept off, Figure 4-11(a) and (b) show that the T and P profile for these 2 cases are almost identical. Furthermore, it can also be observed that the pressure rise across the compressor is significantly higher for both of these cases, allowing maximum expansion through the turbine.

With regards to the hot (24°C) cabin demand case with trim system on (RC3), the PACK-zone controller opens the trim valve and maintains flow through the trim system. This consequently reduces the overall flow through the core of the PACK, as not as much cool air needs to be generated through the ACM as in the previous cases discussed. The only distinction between the hot cases (RC3 and RC7) with trim system on and off is that in the latter case, due to closure of the trim system, the hot bleed air is bypassed using the TCV stream instead of the trim system, see Figure 4-10(a). It is to be noted that the experimental investigation is only focussed on the PACK and at this stage the trim and TCV control logic is not known. As shown in

Table 4-11, the mass flow through the TCV for RC7 is significantly higher (0.265) relative to RC3 with trim system on (0.065). In both cases, ultimately, the flow through the PACK core is reduced in order to limit any unwanted cooling through the ACM, allowing the PACK to comply with the imposed hot cabin demand. The uncertainty error in Table 9 is estimated using:

$$\delta \dot{m}_{\text{TCV_pri}} = \sqrt{\delta \dot{m}_{\text{initial peak at pTCV}}^2 + \delta \dot{m}_{\text{pTCV}}^2} \quad (4-17)$$

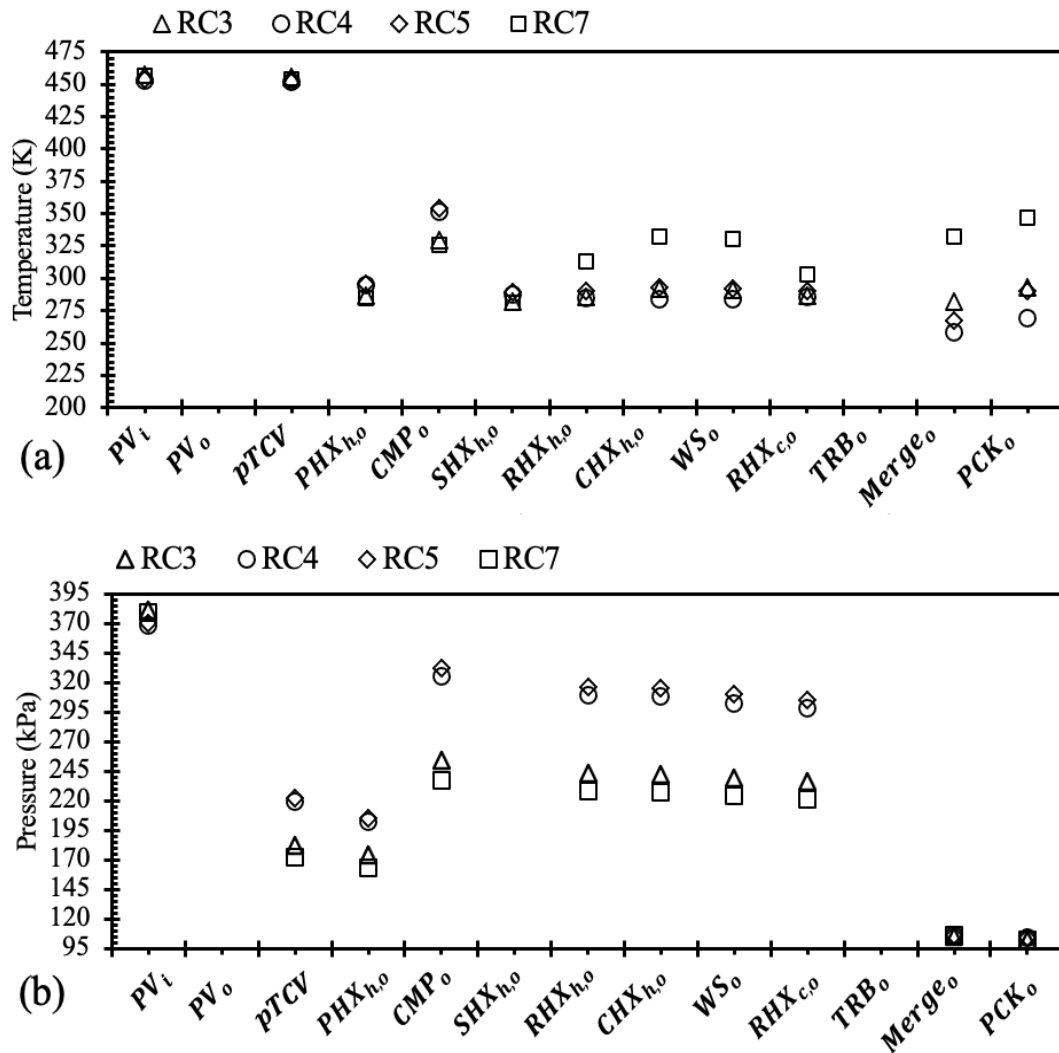


Figure 4-11 (a) Temperature profile and (b) Pressure profile, for selected reference

Table 4-11 Mass flow (kg/s) variation for reference cases with different cabin demand and trim flow status

Reference cases	Cabin demand	Trim Status	TCV-Pri (derived)	$\delta\dot{m}$, TCV-Pri	CMP₀ (measured)	$\delta\dot{m}$, CMP₀	Trim (derived)	$\delta\dot{m}$, Trim
RC3	H	On	0.065	± 0.095	0.340	± 0.054	0.180	± 0.089
RC4	C	On	0.222	± 0.128	0.405	± 0.055	0.035	± 0.114
RC5	C	Off	0.222	± 0.129	0.396	± 0.057	0.044	± 0.117
RC7	H	Off	0.265	± 0.125	0.310	± 0.056	0.010	± 0.122

The GTF have captured the performance characteristics of the PACK under hot and cold demand consistently. The acquired data suggest that under cold demand PACK operation, irrespective of the status of the trim system (on or off), the PACK controller permits maximum mass flow to flow through the core of the PACK in order to maximise the expansion through the turbine. The PACK is found to be operating at 28% higher core mass flow under cold demand compared to the hot demand cases. Based on the acquired data, it can be safely said that under PACK cold demand operation the trim system can be maintained off, as the PACK-zone controller dictates the status of the trim flow, which is found to be same under trim off and trim on condition. With regards to the hot demand PACK operation the data suggest that the PACK-zone controller choses to bypass maximum hot mass flow through the trim system in case if the trim system is on. And in case if the trim system is off, the controller instead uses the TCV to bypass the hot mass flow, in both cases however, the core mass flow is ultimately minimised so that the undesired expansion through the turbine can be maintained minimum.

In terms of capturing the data consistently, the only short fall that can be observed from the data is associated with the WS_o outlet temperature, this temperature is expected to be matched against the imposed demanded temperature as per the AMM [21]. As elaborated in the preceding section, the reasoning for why the PACK controller is unable to match the WS_o temperature against the demanded temperature cannot be comprehended due to lack of access to the employed PACK zone control logic for regulating the WS_o temperature as well as the lack of the performance characteristic of the downstream systems i.e. mixing manifold, air distribution and trim system. Apart from the regulation of the WS_o temperature, the GTF consistently captures the performance characteristics of the PACK components and are found to obey the first principles of the components physics. Furthermore, the data is also able to capture consistently the engineering aspect of the PACK operation in terms of the regulation of the trim system. The acquired data from the consistency test can be used to compare estimations of a physics first principles based simulation

model i.e. SESAC to verify its capability to produce the performance characteristics under various PACK operating conditions.

4.6 Comparison of SESAC Against the SESAC Simulation

Having successfully demonstrated the capability of the GTF to capture the PACK performance characteristics in terms of T , P and $\dot{m}$ under different ambient and operating conditions, in this section the estimation acquired from a simulation model based on the first principles of the components physics are compared against the data acquired through the GTF. The SESAC simulation framework discussed under Section 4.2.3 has been used to develop a reference simulation model for the B737-400 PACK. All the RCs have been simulated and compared against data and RC4, RC5, RC6 and RC7 are selected for demonstration purposes, as these RCs represent the PACK operation under hot and cold demand with trim system on and off and are deemed suitable to test and demonstrate SESAC's capability. First, the employed simulation model and the corresponding boundary conditions for the selected RCs are presented and discussed. Subsequently the overall average relative difference between the test data and simulation is discussed for the selected RCs. Finally, the T , P and $\dot{m}$ test data is corroborated against the simulation at PACK component level.

4.6.1 Reference SESAC Simulation Model

The theoretical and computational development of the SESAC PACK simulation model for a B737-800 has been reported [15,16]. For the implementation of simulation in this chapter, the reported model has been reproduced and is implemented with some modifications in order to represent the B737-400 PACK simulation. The developed B737-400 PACK model is presented in Figure 4-12. In terms of the modifications, a dedicated integral controller has been incorporated to account for the effect of the trim system [20], detailed in Section 2.2. The rest of the model configuration remains identical to the adopted reference model, elaborated in Section 4.2.3.

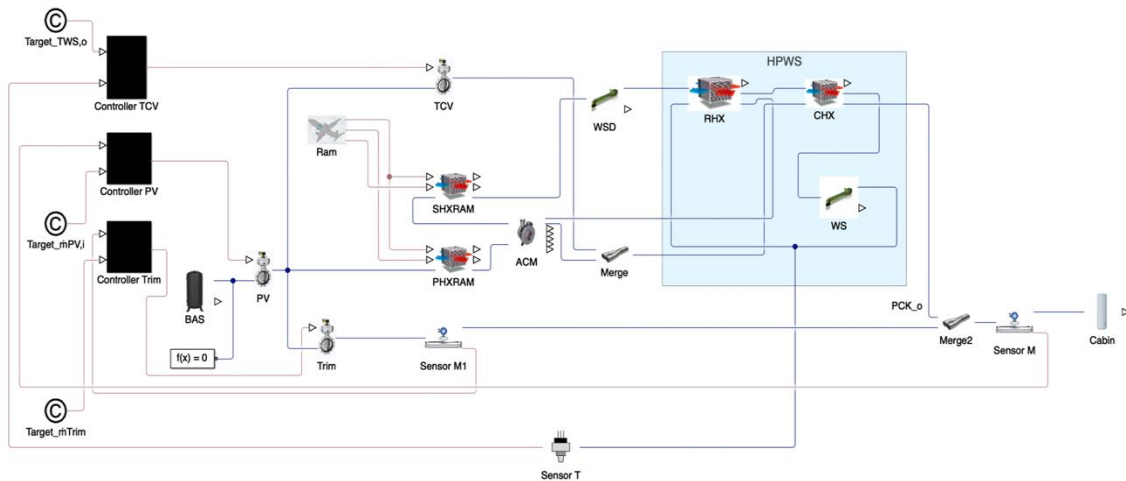


Figure 4-12 Simulation model of the B737-400.

In order to implement the developed simulation model for the selected RCs, boundary conditions must be defined. The overall required boundary conditions for the model simulation can be categorised in five parts, as shown in

Table 4-12. As all the experimental testing was conducted at sea level static conditions, the aircraft state conditions were set to ground operations. The measured ambient condition, and the Ram mass flow derived using energy balance equation as outlined in Section 4.5.3, were defined in the model accordingly for each RC. The bleed air properties (T and P) were taken from the acquired experimental data. The humidity and water content were set to 0, as analysis of the humidity is excluded from this study. To meet the cabin demand, the target temperature was set as the measured WS_o temperature as prescribed in the AMM for the B737-400 PACK architecture [20]. The target mass flow was set as the measured peak value obtained from the pTCV station, which is treated as the inferred PV_i mass flow, as explained in Section 4.5.3. Finally, the trim mass flow derived using Eq. 4-15 is set as a trim flow in the model for each RC. All SESAC simulation were performed with the assumption that the components are free from degradation. Therefore, the DS level for each component was set to 0.

Table 4-12 SESAC PACK simulation model boundary conditions

	Parameters	Description	Units
Aircraft State condition	Selector (S)	0 (Ground operations)	[-]
Ram (0: Ground Static)	$\dot{m}_{RAM}$	Heat-exchanger cold mass flow	[kg/s]
	T_{amb}	Ambient temperature	[K]
Ram (1: In flight)	Alt	Altitude	[m]
	Mach	Mach number	[-]
	Area	Ram door opening area	[m ²]
	%Open	Ram door percentage open	[%]
Bleed Air properties	$PV_i - T$	Bleed temperature	[K]
	$PV_i - P$	Bleed pressure	[Pa]
	$PV_i - SH$	Bleed humidity	[kg/k]
	$PV_i - CO$	Bleed water content	[kg/k]
Target Conditions	$PCK_o - P$	PACK outlet pressure	[Pa]
	$WS_o - T$	Cabin demand/ WS outlet temperature	[K]
	$PV_i - \dot{m}$	Bleed mass flow	[kg/s]
	$\dot{m}_{Trim}$	Trim mass flow	[kg/s]

One important aspect with regards to the simulation worthy of noting at this stage is that, as explained in Section 4.5.3, the PV_i mass flow is inferred based on the peak value measured at the pTCV, therefore any uncertainty associated with the mass flow needs to be accounted for prior to incorporating it in the model as a boundary condition. The method detailed in Section 4.4.3 for uncertainty propagation to mass flow calculation was adopted to determine the estimates for the associated uncertainty error. Figure 4-13(a) presents the acquired peak value at the pTCV station for RC4, RC5, RC6 and RC7 and the respective error bounds for the uncertainty. The estimated uncertainty error range is found to be high and can be attributed due to the use of multiple sensors to measure the acquired T and P for supporting the mass flow calculations. In addition, as reported by the authors in their study dedicated to the evaluation of

the control system of the PACK, it has been demonstrated that the PV maintains a near constant mass flow due to its design dependency on the pressure drop across the valve and the ambient pressure. Therefore, any sudden change in ambient pressure can impose a marginal variation in the mass flow through the PV [20]. The effect of this marginal change in PV_i can also contribute to the overall uncertainty associated with the PV_i mass flow presented in Figure 4-13(a) in addition to the employed instrumentation for measuring the mass flow. In a study reported by Skliros et al. [38], the measurement of bleed mass flow using the two pressure transducers in a Boeing 747 APU lead to a maximum error of around 7%. It was identified that the uncertainty error increased with a decrease in the measured mass flow. Their findings therefore suggested the use of a differential pressure transducer to improve the overall mass flow uncertainty error.

In the similar fashion to the PV_i mass flow, there is uncertainty associated with the measured Ram flow. As elaborated in Section 4.5.3, the Ram mass flow is measured based on the measurements of the temperatures across the cold and hot side of the PHX, and the measured CMP mass flow. The associated uncertainty with these measured quantities will propagate to the Ram mass flow. Using the same method adopted for the uncertainty calculation of the PV_i , the estimate of the uncertainty error associated with the Ram mass flow is calculated for all RCs and is presented in Figure 4-13(b).

Figure 4-13(a) shows the PV_i mass flow values for the simulation, labelled as PV_i (SESAC). It is evident that the PV_i values used for the simulation fall within the overall uncertainty associated with the PV_i mass flow as elaborated earlier. Figure 4-13(b) shows that the Ram mass flow values for the simulation were incorporated without making any alterations across all cases. Therefore, from the overall boundary conditions tabulated in

Table 4-12 only the PV_i mass flow was adjusted in order to attain a consistent match against the overall data in terms of T, P and $\dot{m}$. The pressure

loss coefficients for the HXs (PHX, SHX, RHX, CHX) as well as the mechanical efficiency of the ACM, were maintained fixed throughout the simulation for all cases as reported in previous study on the B737-800 simulation[15]. Table 4-13 presents the incorporated boundary condition values corresponding to all RCS.

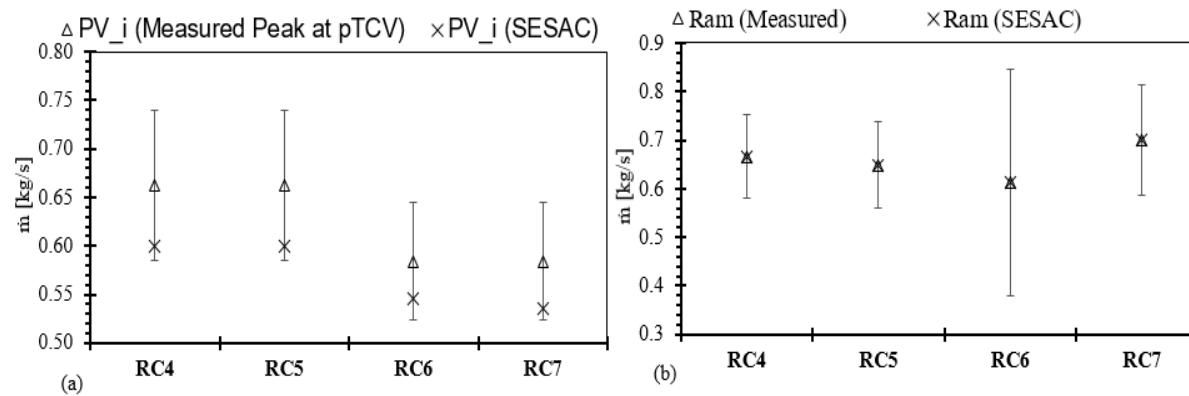


Figure 4-13 PV inlet mass flow uncertainty error for selected RCs

Table 4-13 Boundary condition for the reference cases to run simulation

Reference Cases	PV _i – T (K) (measured)	PV _i – P (kPa) (measured)	PV _i - $\dot{m}$ (kg/s) (inferred + corrected)	$\dot{m}_{Trim}$ (kg/s) (derived)	T _{amb} (°C) (measured)	$\dot{m}_{Ram}$ (kg/s) (derived)	WS ₀ – T (K) (measured)
RC4	453.41	367.94	0.600	0.405	6.5	0.666	283.64
RC5	453.94	369.86	0.600	0.396	6.5	0.649	292.23
RC6	453.04	373.84	0.545	0.180	5.5	0.614	330.40
RC7	456.47	379.54	0.535	0.310	5.5	0.701	330.51

4.6.2 Simulation Average Relative Differences

Prior to proceeding with the detailed analysis of the test data against the simulation it is important to highlight that some discrepancies are inevitable between the simulation and the test data, and can be attributed due to the following reasons [15]:

- i. The intrinsic wear and tear of the system. The Boeing 737 being used is a very old plane and its components are likely to be deteriorated from their new condition.
- ii. The RCs include PACK losses not accounted for in the SESAC, e.g. component leakages and the losses associated with the interconnecting duct sealings.
- iii. Lack of accurate resolution of the system component performance map characteristics incorporated in the SESAC components, i.e. compressor, turbine, heat exchangers.
- iv. The test data may include some level of component fouling in the HXs, or losses in the mechanical efficiency of the ACM. Such losses are extremely difficult to account for in a physics based (theoretical) simulation unless real engineering insight of the system is available. Lack of such engineering knowledge of the system leads to inevitable discrepancies when comparing the simulation predictions against the actual data [15].

Due to these reasons the simulation discrepancies in this work are referred to as the difference rather than the error between the simulation and the test data. Furthermore, with regards to the mass flow data, the mass flow data is derived based on the measured T and P, and the differences in mass flow data therefore also stem from the uncertainly error propagation associated with the T and P measurement, as elaborated in Section 4.4.3.

The results for the simulation and the data for RC4, RC5, RC6 and RC7 in terms of the T, P and $\dot{m}$ are presented in Figure 4-14 and Figure 4-15. These cases present the PACK operation under hot and cold demand with trim system

on and off. It can be seen that broadly the simulation captures the performance characteristics throughout the PACK with good agreement against the data. As observed in the results, in terms of the temperature comparison with the data the $Mer_{g,0}$, and PCK_0 present the highest discrepancies, and in terms of the pressure the highest discrepancies occur across the ACM. The areas of discrepancies between simulation and data are consistent across all cases, which indicates the underlying reasons to be the same. This implies that the overall behaviour of the simulation model against the data remains consistent under different PACK operating conditions.

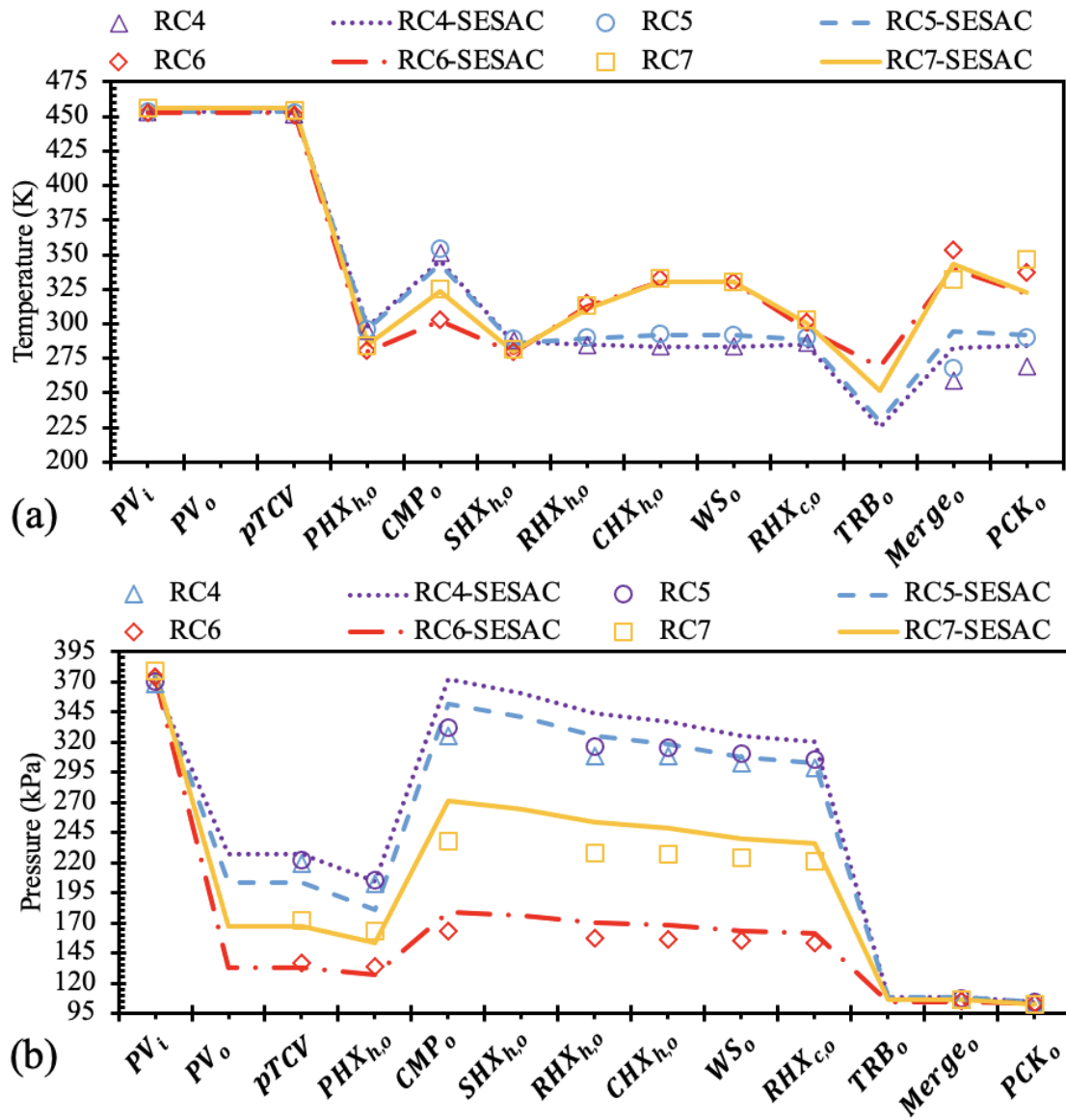


Figure 4-14 (a) Temperature profile and (b) Pressure profile for RC4, RC5, RC6 and RC7

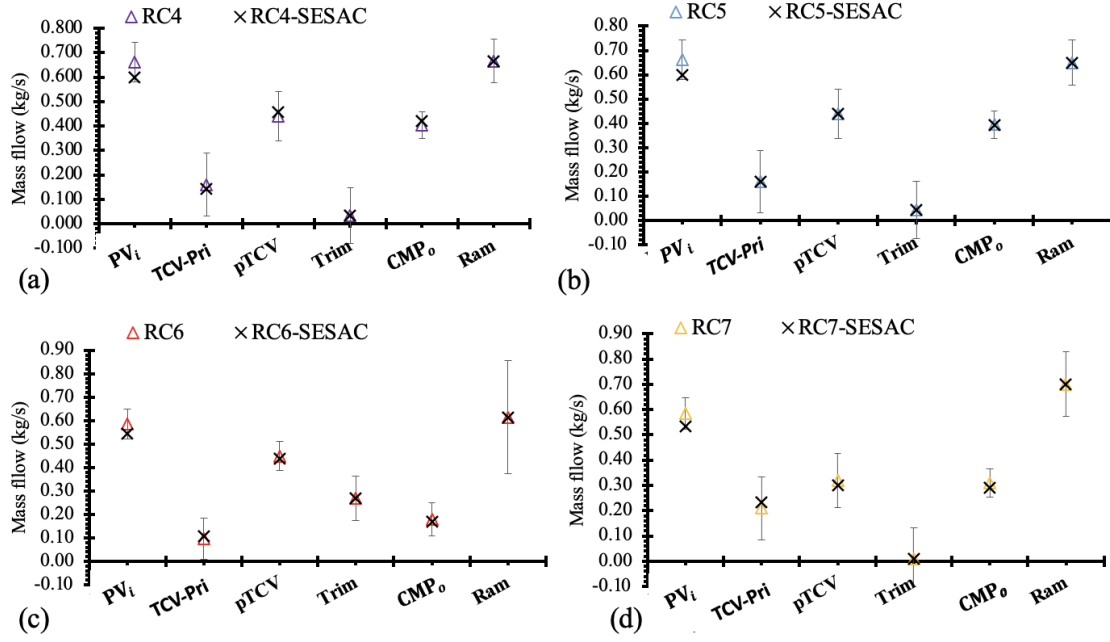


Figure 4-15 Mass flow measurement and simulation data for (a) RC4 (b) RC5, (c) RC6 and (d) RC7

Prior to proceeding with the analysis at the component level between the data and the simulation, it is deemed practical to first evaluate the average relative difference for T, P and $\dot{m}$. To do this, Eq. 4-18 is applied to calculate the relative difference for T, P and $\dot{m}$ at each measurement location between the simulation and the test data throughout the PACK. The measurement locations are depicted in Figure 4-2. The sum of the difference for these variables is then used to calculate the average relative difference for each parameter by using Eq. 4-19. Therefore, the average relative difference represents the overall difference between the simulation and test data with respect to T, P and $\dot{m}$ for each corresponding RC [15].

$$\text{Rel. Difference} = \frac{(\text{Model} - \text{actual data})}{\text{actual data}} \times 100 [\%] \quad (4-18)$$

$$\text{Average Rel. Difference} = \frac{\sum \text{Model Rel. Diff at each station}}{\text{number of stations}} \times 100 [\%] \quad (4-19)$$

Figure 4-16 presents the calculated average relative difference for all the RCs selected (RC4, RC5, RC6 and RC7). The maximum average relative difference between the simulation and data in terms of T, P and $\dot{m}$ across all RCs

is found to be 2%, 8% and 6% respectively. These results show that the model can capture the overall temperature variation across the PACK with higher accuracy compared to pressure and mass flow variation. The higher model accuracy for temperature can stem from the fact that the heat exchanger effectiveness maps incorporated within SESAC are able to capture the performance characteristics of the PACK operating under ground conditions. This finding is consistent with the SESAC PACK 737-800 analysis carried out under cruise conditions [15]. With regards to the differences associated with the pressure and mass flow, these are evaluated in detail by assessing the temperature, pressure and mass flow throughout the PACK in the following section for one of the selected RCs, i.e. RC4

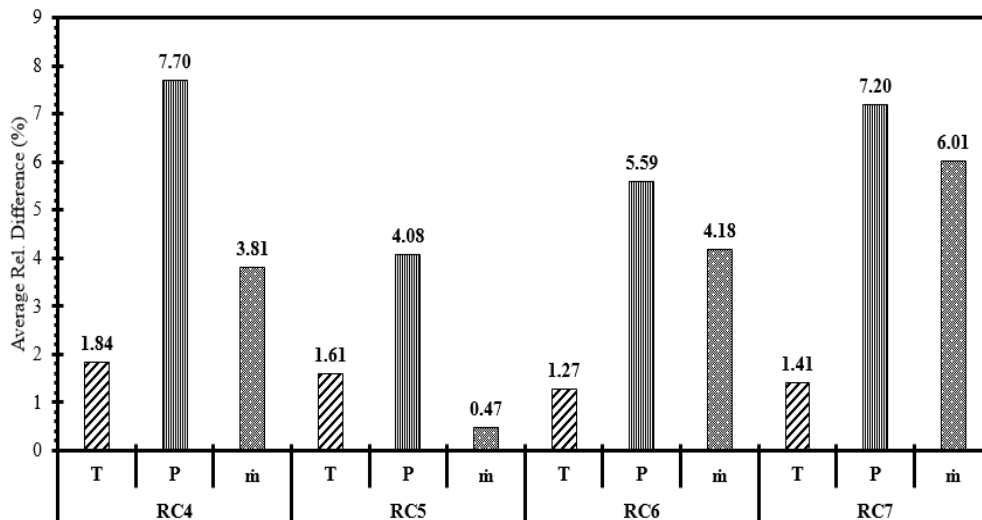


Figure 4-16 Average relative difference calculated for RCs with respect to T, P and m

4.6.3 Reference Case 4 Analysis and Discussion

Figure 4-17 presents the results for the simulation and the test data for T, P and m corresponding to RC4 at component level throughout the PACK. In order to systematically report the corroboration of the overall simulation estimates against the test data, first the situation related to the incorporation of the PV inlet and Ram mass flow needs to be clarified. As explained in Section 4.6.1, the model requires PV inlet and Ram mass flow as boundary conditions. Ram mass flow dictates the cold mass flow through the PHX and SHX, PHX and SHX, whereas

the PV_i mass flow dictates how the overall energy is distributed through the PACK core in order to condition the flow against the demanded temperature. Depending on the demanded temperature, the overall PV_i mass flow is distributed through the hot stream and cold stream of the PACK. Hot streams are represented by the TCV and trim bypass channels, whereas the flow through the core of the PACK represents the cold stream, as illustrated in Figure 4-2, and is responsible for the conditioning of the flow.

In order to accomplish a reasonable agreement between the simulation and the data, it is vital to match the overall distribution of the mass flow through the hot and cold streams of the PACK as well as the Ram flow through the PHX and SHX. The data provides measured mass flow through the core, measurements at the CMP_o station. With regards to the flow through the hot stream, an estimation of the trim mass flow can be attained based on the measured mass flow at pTCV and CMP_o station, see Eq. 4-15. For the purpose of simulation, an initial guess for the PV_i mass flow was made based on the inferred peak value measured at the pTCV station, and while keeping the measured Ram mass flow value fixed through the PHX and SHX, the PV_i value was iteratively changed until a good match for the mass flow through the core of the PACK (at CMP_o station) was attained against the data.

Figure 4-17(c) shows the data and simulation mass flow values for RC4 at measured, derived and inferred stations. It is evident that the PV_i inferred value was adjusted in order to match the measured core mass flow through the PACK. The difference between the simulation and the data at CMP_o is 3.9% and falls within the uncertainty error range represented by the error bars. This was deemed as best match between the simulation and the data, as it leads to a perfect agreement for temperature throughout the core components of the PACK, as well as a reasonably acceptable match for the pressure considering the limitations associated with the resolution of the incorporated turbomachinery maps.

For the temperature profile shown in Figure 4-17(a), the simulation results are in good agreement with the data throughout the PACK, except the merge and PACK outlet stations. The overall average relative difference for the temperature

is 1.84% and predominantly stems from the discrepancies occurring at the merge and PACK outlet stations, highlighted as dotted red circle in Figure 4-17(a). At the merge component (Figure 4-2), continuity and energy have to be satisfied. Referring to the flow through the heat exchangers and ACM as 'cold', these equations are:

$$\dot{m}_{PV_i} = \dot{m}_{cold} + \dot{m}_{TCV_pri} + \dot{m}_{Trim} \quad (4-20)$$

$$\dot{m}_{PV_i} C_p T_{target} = \dot{m}_{cold} C_p T_{cold} + \dot{m}_{TCV} C_p T_{TCV} + \dot{m}_{Trim} C_p T_{Trim} \quad (4-21)$$

In addition, as there can be no pressure discontinuity at the merge, the pressure at the turbine outlet, the TCV outlet, and merge outlet are the same. The measured PACK outlet pressure, which is marginally lower than the merge outlet is imposed as the PACK outlet boundary condition in the model. This imposes a requirement on the turbine to produce the required expansion in order to match the downstream pressure of the data. Note that, in terms of the inlet conditions of the turbine, the temperature of the flow remains the same between the simulation and data, however the simulation has a 7.4% and 3.9% higher pressure and mass flow through the turbine relative to the data. This will inevitably result in higher expansion through the turbine, and therefore higher temperature drop across the turbine. With these temperature differences at the turbine outlet, the energy balance between the data and the simulation lead to prominent discrepancies at merge and PACK outlet stations.

The measured PACK inlet temperature is introduced as the inlet boundary condition in the simulation model. The simulation provides the estimate for the PV outlet temperature and suggests that the temperature remains constant through the PV. Temperature data was not collected at PV outlet, instead, the measurement of the temperature was taken at pTCV, which corresponds to the location immediately downstream of the TCV bypass. Since the TCV flow extraction has no impact on the temperature, the measurement at the pTCV station represents the PV outlet temperature. The data suggests that as the flow travels through the PV and approaches the pTCV station, it has a marginal (2K) drop in its temperature, which can be attributed to heat loss. However, the

simulation is based on the assumption that these losses are negligible and can be safely omitted.

Downstream of the pTCV station, the flow enters the PHX, which significantly cools the air by using the Ram flow as a heat sink. It can be seen that the temperature drop across the PHX is well matched by the simulation. Note, the Ram flow for the simulation is introduced in the model based on the measured Ram mass flow data, and as shown Figure 4-13(b) the incorporated Ram mass flow simulation values were maintained exactly the same as the ones measured for the corresponding cases. This suggests that the effectiveness maps incorporated in SESAC are a good representation of the performance characteristics of the aircraft PHX. This trend remains for all the heat exchangers throughout the PACK, i.e. SHX, RHX, and CHX, as the simulation estimates the change in temperature across all heat exchangers quite accurately, as shown in Figure 4-17(a). Figure 4-18 presents the acquired effectiveness values for all the heat exchangers for the simulation against the data; good agreement between experimental data and simulation is observed.

In terms of the pressure drop across the heat exchangers, Figure 4-19 presents the simulation estimates for the pressure drop across the heat exchangers against the data. The measured value for the SHX is not included, as the pressure is not measured there. The simulation reasonably captures the pressure drop across the RHX and CHX, implying that the implemented pressure loss coefficients are reasonable, and may require some fine tuning for the CHX. With regards to the PHX, the simulation over predicts the pressure drop by 3.75% relative to the data. Which implies that the employed friction coefficient may require some fine tuning in order to match the pressure drop. Another reason for the over prediction could also be due to the differences in the core mass flow (simulation being 3.9% higher) between the simulation and the data. It is interesting to note that, although the PHX and SHX are identical units in terms of their design, size, and shape, the pressure drop across the SHX is significantly lower relative to the PHX. This stems from the fact that the inlet conditions of the SHX with significantly lower temperature and higher pressure relative to PHX

leads to increased air density (see Eq. 4-6) which consequently reduces the friction coefficient (see Eq. 4-22) and influences the loss coefficient (see Eq. 4-23) resulting in lower pressure drop across the SHX [15,39]. This broadly explains the pressure characteristics of the heat exchangers throughout the PACK.

$$f = \frac{\tau_w}{\frac{1}{2} \rho v^2} \quad (4-22)$$

$$k = f \frac{L}{D_H} \quad (4-23)$$

With regards to the differences associated with the ACM, as already established, the simulation has a 3.9% higher mass flow through the ACM. The simulation incorporates the performance maps for the compressor and turbine, which determine the ACM operating point in order to match the work balance between the compressor and turbine that are mounted on the same shaft. The maps corresponding to the B737-400 aircraft could not be attained due to propriety reasons, therefore the simulations were conducted based on readily available maps incorporated for the simulation of the B737-800 PACK [15]. This can be one of the likely reason along with the differences in the mass flow through ACM that the acquired performance characteristics of the ACM could not be matched consistently against the data in terms of temperature and pressure. The simulation over predicts the compressor pressure ratio, which stems from the fact that due to higher mass flow through the turbine, the power produced by the turbine to drive the compressor is significantly higher than required. Without having representative maps for the AMC these differences in the mass flow and pressure are inevitable from the simulation point of view. Note, a good agreement is attained between the simulation and data in terms of the temperature rise across the compressor. The engineering explanation behind why the over prediction of the compressor pressure does not consistently lead to over prediction of temperature rise through the compressor is not understood. The differences in the pressure at the compressor outlet is found to propagate through the high pressure HPWS i.e. RHX, CHX.

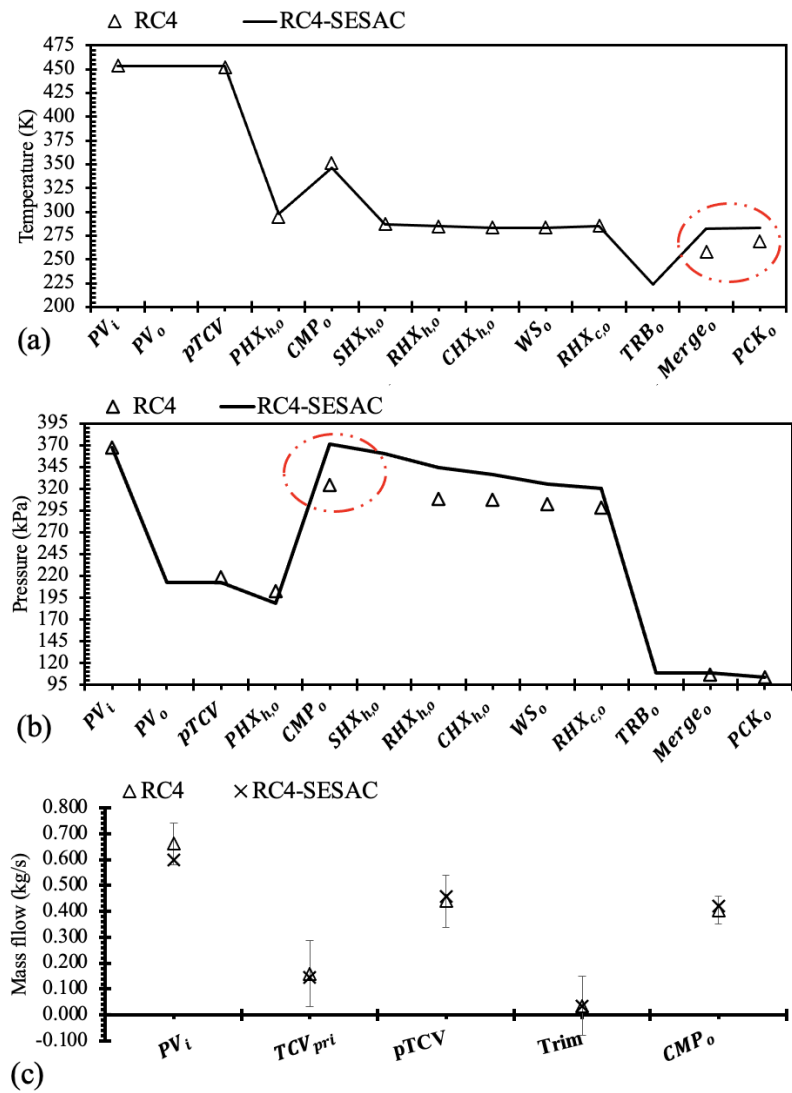


Figure 4-17 (a) Temperature profile, (b) Pressure profile and (c) Mass flow for RC4

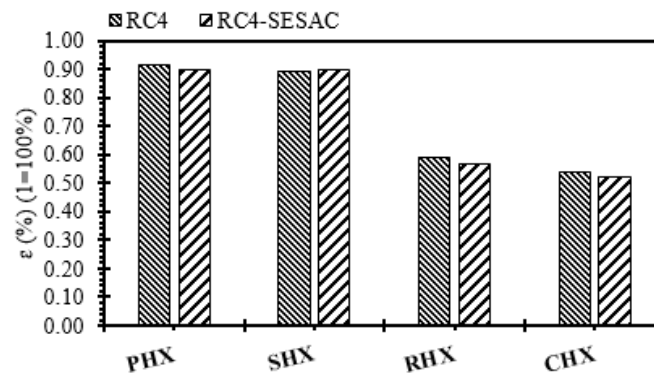


Figure 4-18 Effectiveness calculated using data and simulation for the heat exchangers

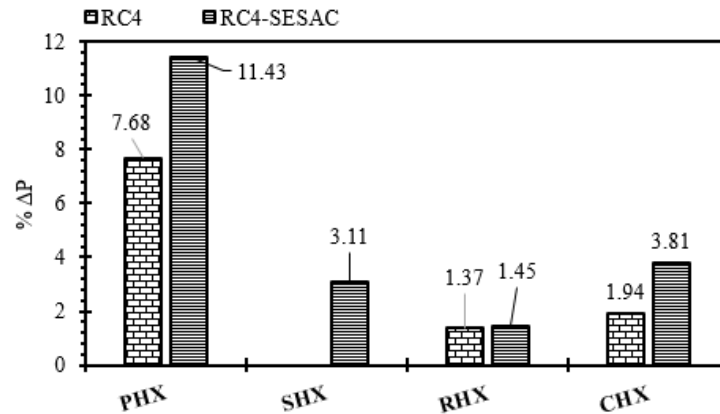


Figure 4-19 Experimental and simulated pressure drop across the heat exchangers

4.7 Summary and Conclusions

In this chapter the development of a novel in-situ ground test facility for the experimental investigation of a civil aircraft ECS has been reported. The Cranfield University's ground demonstrator aircraft B737-400 has been instrumented with temperature, pressure, humidity, valve rotary sensors, and data acquisition unit. The validation of the GTF for generating temperature, pressure and mass flow data has been demonstrated based on the data repeatability and consistency tests conducted under different ambient conditions and PACK operating modes. The installed sensor measurement uncertainty and its propagation has been thoroughly evaluated and incorporated as part of the overall data acquisition process.

The outcome of the sensor uncertainty analysis suggests that the temperature sensors have very low measurement uncertainty compared to the pressure sensors. The error propagation from these pressure transducers results in a higher uncertainty in mass flow measurement due to the use of multiple sensors, and therefore it has been identified that differential pressure transducers should be considered in order to enhance the overall measurement uncertainty. Installation of the pitot probes for the Ram mass flow measurements failed to provide usable data due to their installation at the inlet of the PHX, a pitot static tube installed in the Ram duct is deemed to address this shortfall.

The acquired data from the repeatability and consistency test suggest that the GTF is able to generate data that captures PACK components functional outputs under different ambient conditions and operating modes. The acquired temperature, pressure and mass flow data is found to obey the first principles of physics associated with the PACK components design and integration. The engineering characteristics of the PACK operation in terms of the control system logic for TCV and trim mass flow are found to be consistently captured by the GTF under the consistency tests. However, the control of the WS_o outlet temperature could not be captured by the GTF under both repeatability and consistency tests. The elaboration of acquired data for repeatability and consistency therefore strongly emphasize that without insights on the inbuilt control logic of the WS_o temperature regulation and the performance characteristics of the upstream and downstream systems (i.e. bleed air, mixing manifold, air distribution, and trim system) a systematic repeatability and consistency of the PACK control characterises cannot be attained.

From the PACK experimental investigation perspective, one of the key learning resulted from this study is the realisation of the role of upstream, downstream systems, and the PACK-zone controller on the PACK components performance characteristics. The second key learning is towards the realisation of the impact of trim system on the performance characteristics of the PACK core components specifically the ACM. The trim system can substantially impact the amount of compression and expansion through the ACM and therefore the amount of cooling that can be attained under given PACK demand. The tests conducted for trim system under various PACK demands suggest that the trim system under cold demand have no practical implication on the PACK performance and can therefore be maintained off. However, under the hot demand cases, having the trim system on can influence the performance characteristics of the PACK which favours the PACK ACM to operate compatibly under hot demand.

The acquired data is further compared against the estimates of PACK performance characteristics (i.e. temperature, pressure and mass flow) under

various PACK operating modes derived based on a physics based simulation model (SESAC). The estimates acquired from the simulation were found to be in good agreement with the data in terms of the temperature throughout the PACK except for the merge outlet and pack outlet temperature stations. With regards to the pressure, the required results suggest that the pressure characteristics of the components mounted upstream of the compressor are in reasonable agreement with the data, however due to inevitable differences in the incorporated ACM components performance maps, the compressor and the downstream components pressure characteristics could not be well aligned against the data. Overall, the maximum average relative difference between the simulation and data in terms of T, P and $\dot{m}$ across all reference cases is found to be 2%, 8% and 6% respectively. This was deemed as best match between the simulation and the data, as it leads to a perfect agreement for temperature throughout the core components of the PACK, as well as a reasonably acceptable match for the pressure considering the limitations associated with the resolution of the incorporated turbomachinery maps.

References

1. Figueroa DV. Diagnostic Capability for Environmental Control Systems. Universidad Politécnica de Madrid, Cranfield Univeristy; 2017.
2. Wright S., Andrews G., Sabir H. A review of heat exchanger fouling in the context of aircraft air-conditioning systems, and the potential for electrostatic filtering. *Applied Thermal Engineering*. 2009. pp. 2596–2609. Available at: DOI:10.1016/j.applthermaleng.2009.01.002
3. Ma J., Lu C., Liu H. Fault diagnosis for the heat exchanger of the aircraft environmental control system based on the strong tracking filter. *PLoS ONE*. 2015; 10(3): 1–11. Available at: DOI:10.1371/journal.pone.0122829
4. Jonsson GR., Lalot S., Palsson OP., Desmet B. Use of extended Kalman filtering in detecting fouling in heat exchangers. *Interantional Journal of Heat and Mass Transfer*. 2007; 50: 2643–2655. Available at: DOI:10.1016/j.ijheatmasstransfer.2006.11.025

5. Jonsson G., Palsson OP. An application of extended kalman filtering to heat exchanger models. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*. 1994; 116(2): 257–264. Available at: DOI:10.1115/1.2899218
6. Santos APP., Andrade CR., Zaparoli EL. A thermodynamic study of air cycle machine for aeronautical applications. *International Journal of Thermodynamics*. 2014; 17(3): 117–126. Available at: DOI:10.5541/ijot.538
7. Ma Z., Zhang X., Wang C., Yang H., Yang C. Study on Ground-Test Simulation Method of the Ram Air for Commercial Airlines' Environmental Control System. *Procedia Engineering*. Elsevier B.V.; 2015; 121: 325–332. Available at: DOI:10.1016/j.proeng.2015.08.1075
8. Burroughs JD., Hammond RA. Control Analysis and Design Features of EASY5. *American Control Conference*. San Francisco; 1983. pp. 58–63. Available at: DOI:10.23919/ACC.1983.4788072
9. Steinkellner S., Andersson H., Gavel H., Krus P. Modeling and Simulation of Saab Gripen's Vehicle Systems. *AIAA Modeling and Simulation Technologies Conference*. Reston, Virigina: American Institute of Aeronautics and Astronautics; 2009. pp. 1–15. Available at: DOI:10.2514/6.2009-6134
10. C. Müller, D. Scholz TG. Dynamic Simulation of Innovative Aircraft Air Conditioning. *1st CEAS European Air and Space Conference*. 2007. pp. 869–878.
11. Scholz D., Giese T., Erdmann C. Flecs: Functional Library of the Environmental Control System – a Simulation Tool for the Support of Industrial Processes. *AST 2007*, March 29-30, Hamburg, Germany. 2007.
12. Tu Y., Lin G. Dynamic Simulation of Humid Air Environmental Control System. *40th International Conference on Environmental Systems*. 2010. pp. 1–10. Available at: DOI:10.2514/6.2010-6305

13. Tu Y., Lin GP. Dynamic Simulation of Aircraft Environmental Control System Based on Flowmaster. *Journal of Aircraft*. 2011; 48(6): 2031–2041. Available at: DOI:10.2514/1.C031433
14. Steinkellner S. Aircraft vehicle systems modeling and simulation under uncertainty. LINKÖPING University; 2011.
15. Jennions I., Ali F., Miguez ME., Escobar IC. Simulation of an aircraft environmental control system. *Applied Thermal Engineering*. May 2020; 172: 114925. Available at: DOI:10.1016/j.applthermaleng.2020.114925
16. Jennions I., Ali F. Assessment of Heat Exchanger Degradation in a Boeing 737-800 Environmental Control System. *Journal of Thermal Science and Engineering Applications*. 1 December 2021; 13(6). Available at: DOI:10.1115/1.4050324
17. Childs T., Jones AB., Chen R. Development of a Full Scale Experimental and Simulation Tool for Environmental Control System Optimisation and Fault Detection. 2015; : 0–11. Available at: DOI:10.2514/6.2015-1196
18. Esperon-Miguez M., Jennions IK., Escobar IC., Hanov N. Simulating faults in a Boeing 737-200 Environmental Control System using a thermodynamic model. *International Journal of Prognostics and Health Management*. 1 June 2019; 10(2): 1–12. Available at: DOI:10.36001/ijphm.2019.v10i2.2731
19. Boon T. How Many Boeing 737 Aircraft Are Currently In Service & Stored? 2020. Available at: <https://simpleflying.com/boeing-737-in-service-stored/> (Accessed: 30 December 2021)
20. Chowdhury S., Fakhre A., Jennions IK. Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate Fault Simulation. *Journal of Thermal Science and Engineering Applications*. 2 February 2022; : 1–18. Available at: DOI:10.1115/1.4053740
21. Boeing 737-300/400/500 Aircraft Maintenance Manual, D6-3758.

22. Chowdhury S., Ali F., Jennions I. A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics. Proceedings of the Annual Conference of the PHM Society 2019. 2019. pp. 1–11. Available at: DOI:<https://doi.org/10.36001/phmconf.2019.v11i1.888>
23. Omega. Temperature Isolation Coil for G1/4 & 1/4 NPT Pressure Sensor. 2021. Available at: <https://www.omega.co.uk/pptst/PXM-COIL.html> (Accessed: 14 December 2021)
24. Appmeas. How can you protect sensors against high-temperature media? 2021. Available at: <https://appmeas.co.uk/resources/pressure-measurement-notes/how-can-you-protect-sensors-against-high-temperature-media/> (Accessed: 14 December 2021)
25. Inc. HI. PX2 Series Heavy Duty Pressure Transducers. 2021. Available at: https://www.mouser.co.uk/datasheet/2/187/honeywell_sensing_heavy_duty_pressure_px2_series_d-2821546.pdf (Accessed: 14 December 2021)
26. Omega. Pt100 RTD & Thermocouple Probes for Industrial Applications. 2021. Available at: <https://br.omega.com/omegaFilesUK/temperature/pdf/T3PROBES.pdf> (Accessed: 14 December 2021)
27. TE Connectivity. HTM2500LF – Temperature and Relative Humidity Module. 2021. Available at: <https://www.te.com/usa-en/product-CAT-HSA0001.html?q=&d=483080&type=products&samples=N> (Accessed: 14 December 2021)
28. Kirkup L., Frenkel RB. An Introduction to Uncertainty in Measurement. Cambridge: Cambridge University Press; 2006. Available at: DOI:10.1017/CBO9780511755538
29. Variohm. Working Principal of a Pressure Sensor. 2016. Available at: <https://www.variohm.com/news-media/technical-blog-archive/working-principle-of-a-pressure-sensor>

30. UMD. Random vs Systematic Error. University of Maryland. Available at: <https://www.physics.umd.edu/courses/Phys276/Hill/Information/Notes/ErrorAnalysis.html>
31. Solinst. Understanding Pressure Sensor Accuracy, Precision, Resolution & Drift. 2021. Available at: <https://www.solinst.com/onthelevel-news/water-level-monitoring/water-level-datalogging/understanding-pressure-sensor-accuracy-precision-resolution-drift/> (Accessed: 23 November 2021)
32. Inc. HI. Auto-Zero Calibration Technique for Pressure Sensors. 2018. pp. 1–10. Available at: <https://sensing.honeywell.com/auto-zero-calibration-technique-pressure-sensors-technical-note.pdf>
33. Peters CA. Statistics for Analysis of Experimental Data. In: Powers SE (ed.) Environmental Engineering Processes Laboratory Manual. AEEESP; 2001. Available at: https://www.researchgate.net/publication/280580217_Statistics_for_Analysis_of_Experimental_Data
34. Taylor JR. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. Second. University Science Books; 1998. Available at: http://hep.ucsb.edu/courses/ph128_18f/Taylor.pdf
35. Kim H-Y. Statistical notes for clinical researchers: assessing normal distribution (2) using skewness and kurtosis. Restorative Dentistry & Endodontics. 2013; 38(1): 52. Available at: DOI:10.5395/rde.2013.38.1.52
36. Mishra P., Pandey C., Singh U., Gupta A., Sahu C., Keshri A. Descriptive statistics and normality tests for statistical data. Annals of Cardiac Anaesthesia. 2019; 22(1): 67. Available at: DOI:10.4103/aca.ACA_157_18
37. Harvard University Department of Physics. A Summary of Error Propagation. 2007. pp. 3–7. Available at: http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf
38. Skliros C., Ali F., Jennions I. Experimental investigation and simulation of a boeing 747 auxiliary power unit. Journal of Engineering for Gas Turbines

and Power. 2020; 142(8). Available at: DOI:10.1115/1.4047771

39. Luyben WL., Tuzla K. Gas Pressure-Drop Experiment. Chemical Engineering Education. 2010; : 183–188. Available at: <https://eric.ed.gov/?id=EJ935038>

5 Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate Fault Simulation

‘An equation means nothing to me unless it expresses a thought of God.’

- Srinivasa Ramanujan

The aircraft environmental control system (ECS) is a highly integrated and complex system. The passenger air conditioner (PACK) is the heart of the ECS and has been reported as a key driver of unscheduled maintenance by aircraft operators. This is principally due to the PACK's ability to compensate for degraded components, and hence mask their real condition, so that when failure occurs it is a major event. The development of an accurate diagnostic solution would identify the degradation early and hence focus effective maintenance and reduce cost. This chapter is a continuation of the previous work on the development of a systematically derived PACK simulation for accurate fault diagnostics, utilising a model-based approach. In practise the PACK simulation accuracy is dependent on a number of factors, which include the understanding of its control system. This chapter addresses this by taking an in-depth look at the factors controlling the operation of the PACK in order to enable the gap between the theoretical understanding of the PACK and the engineering design of the system to be bridged, and accurate simulations under healthy and degraded scenarios obtained. The chapter provides a comprehensive explanation of the PACK control system elements (principally valves) and verifies their operation based on experimental test data acquired from a B737-400 aircraft. A discussion of the control used in the simulation is then given, resulting in the correct temperature, pressure and flow being delivered to the cabin. The overall simulation results are then presented to demonstrate the importance of employing a systematically derived control logic. They are then further used to assess the impact of degradation in the main PACK valves.

Table 5-1 shows the table of content of this chapter. This chapter is published in the Journal of Thermal Science and Engineering Applications (see list of publications in section 1.6).

Table 5-1 Overview of Chapter 5

5.1	Introduction
5.2	PACK Control System
5.3	PACK Simulation Model and Controller
5.4	Results & Discussion
5.5	Conclusions

5.1 Introduction

All commercial aircraft are equipped with an air conditioning system, commonly known as the Environmental Control System (ECS). The ECS is responsible for two key functions: (i) providing pressurised air to the anti-icing system, and: (ii) regulating cabin temperature (T), pressure (P) and humidity. The heart of the ECS is the Passenger Air Conditioner (PACK), whose components are prone to degradation, with operators reporting the PACK to be one of the key drivers of unscheduled maintenance. The overall functionality of the PACK is dependent on the synergistic operation of various sub-systems - heat exchangers, valves, a compressor and a turbine - making it a complicated system with maintenance problems that may not have a clear root cause. Recent studies of the ECS have reported strong interdependencies between the sub-systems of the PACK, specifically when subjected to degradation [1,2]. Furthermore, the PACK control system focusses the performance characteristics of the PACK sub-systems on set targets, and therefore has the potential to mask degradation in its components [1]. For these reasons the determination of accurate control logic is vital for capturing the physics of the system operating in healthy and faulty scenarios.

There is a compelling requirement from industry to identify innovative retrofit Condition Based Maintenance (CBM) solutions for supporting a robust

maintenance strategy on legacy aircraft [3]. Model-based approaches for diagnosis have been predominantly used and purposed for CBM implementation, due to their intuitive engineering approach. This includes identification of sensor set optimisation, followed by calculation of the difference between sensor data and model data to isolate fault occurrences at sub-system level [4–6]. A simulation model that can accurately capture the physics and engineering of the PACK at sub-system level, under a wide range of functional scenarios, is required, both to focus maintenance activities and reduce cost. In collaboration with Boeing, the IVHM Centre at Cranfield University is conducting research on the ECS and has developed an ECS simulation model: Simscape ECS Simulation under all Conditions (SESAC) [7]. Based on the successful implementation of SESAC, the performance evaluation of the PACK under healthy, and some degraded, operating scenarios have been studied by Jennions and Ali [1].

The thermodynamic performance characteristics of the PACK sub-systems such as the Ram heat exchangers, the bleed flow control valve, the Temperature Control Valve (TCV) as well as the Air-Cycle Machine (ACM) are found to be strongly influenced by the control logic employed within the simulation model, especially when components are exposed to degradation. In order to implement accurate control over the PACK it is necessary to understand not only the objective goals of the system but also the detailed operation of some of the sub-systems, i.e. valves, thus providing the focus for this chapter. [1,7]

5.1.1 Scope of work

Previous papers on SESAC have detailed the construction of an ECS simulation code, capable of replicating healthy flight conditions and some cases of component degradation [1,7]. In practise this simulation is only as good as the understanding of the control system allows, and the availability of experimental data for validation. This chapter addresses the first of these, taking an in-depth look at the factors controlling the operation of the PACK in order to have the

highest possible confidence in the validity of the simulations, specifically when simulating degradation at sub-system level.

In order to understand the PACK control system, it has proved necessary to understand the engineering of the overall control logic and some of the PACK elements, to enable the gap between the theoretical understanding of the PACK and the original design of the system to be bridged. For the aircraft under study, the Boeing 737-400 (B737-400), the PACK control logic is composed of the following elements:

- i. Operation of the PACK bleed flow control valve, known as the PACK Valve (PV)
- ii. A built-in overheat protection system
- iii. Operation of the temperature control valves (TCV)
- iv. Control over the Ram air that provides cold air to the heat exchangers

All these topics are appropriately addressed in this chapter. The chapter provides a comprehensive explanation of the PACK control system elements and verifies their operation based on experimental test data acquired from the B737-400 aircraft. PACK simulation results are presented to substantiate the importance of employing systematically derived control logic to enable accurate fault simulation. Finally, simulations are conducted to assess the degradation in control system elements, i.e. PV and TCV.

5.1.2 Overview of the ECS and PACK Functionality

The ECS is powered by bleed air supplied by the main engines or the APU. The PACK, a schematic of which is shown in Figure 5-1, is the core of the ECS; it conditions the bleed air depending on aircraft cabin demand. Following the PACK, the Air Distribution System (ADS) filters and distributes the conditioned air to the cockpit, cabin and avionics bay. There are normally two PACKs in most narrow and wide-body civil aircraft, both PACKs are generally installed in parallel on either side of the aircraft centreline, on the underside of the fuselage.

Following the sequence of the flow and station numbers shown in Figure 5-1, the PACK PV_i receives bleed air at high temperature and pressure, primary

cooling takes place in the PHX, and secondary cooling takes place in the SHX, the flow is subsequently compressor in the compressor (CMP_o). Cold Ram air labelled as $PHX_{c,i}$ and $SHX_{c,i}$, which originates from outside the aircraft, flows through the Ram air duct and, after being used as a heat sink for PHX and SHX, is deposited back into the aircraft's airstream. After the SHX the temperature of the bleed air has been substantially reduced and is passed through a series of heat exchangers within the HPWS in order to treat the air for humidity. Subsequent to that, the high pressure flow is expanded through a turbine. At the outlet of the turbine (TRB_o) the air temperature can potentially drop below freezing and, if this occurs, it is addressed by mixing part of the bypass hot bleed flow through the TCV-Pri. The mixing of this air is controlled in order to match the PACK outlet temperature against the cabin demand, this temperature is generally referred to as the target temperature (T_{target}) [7].

The PV and TCV in the PACK regulate the hot mass flow through the system and the core in order to sufficiently support the overall functionality of the PACK. This requires a number of control logic paths in order to regulate the valve positions which will be investigated in this chapter.

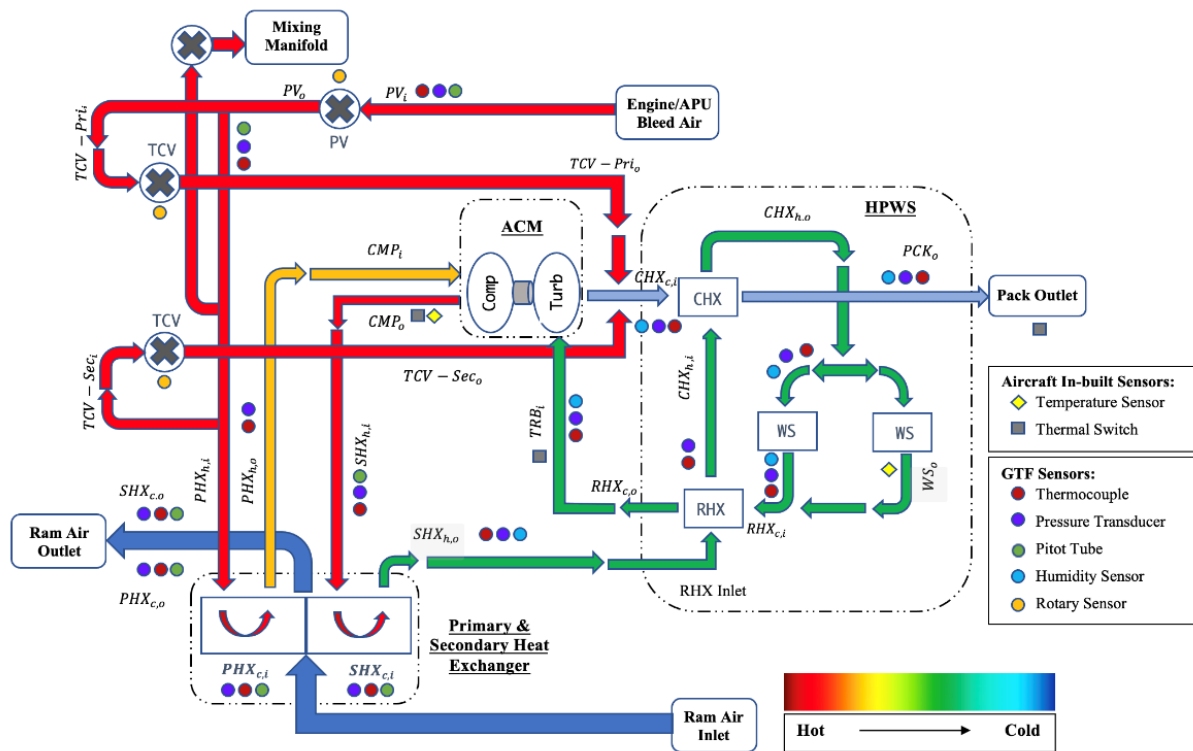


Figure 5-1 Component level schematic of the B737 PACK with the labelling of the airflow sequence.

5.1.3 PACK Simulation Framework - SESAC

SESAC is a simulation framework that offers the implementation of an object-oriented modelling approach, enabling a drag-and-drop interface, where each component of the ECS is independently formulated. This approach allows the flexibility to integrate components together to represent an overall ECS system, allowing the acquisition of system performance parameters at each component's inlet and outlet. Furthermore, SESAC provides component sub-libraries, e.g. a dedicated library is assigned to represent healthy and faulty components, and the ability to input component design characteristic maps [7].

SESAC is capable of simulating the performance characteristics of the ECS under a wide range of operating conditions and functional scenarios. Fault severities can be introduced to each component, and multiple faults can be simulated simultaneously. The theoretical and computational development of SESAC has been previously reported by Jennions et al. [7].

5.1.4 Boeing 737 Ground Test Facility

A full scale Boeing 737-400 aircraft ground test facility has been developed at Cranfield University. The aircraft major sub-systems, such as the ECS and APU, have been instrumented with various types of condition monitoring sensors [8]. These sensors allow the acquisition of system health state parameters at sub-system level.

The left-side PACK of Cranfield's B737, as shown in Figure 5-2, has been instrumented with sensors in order to measure pressure, temperature, mass flow (T , P , $\dot{m}$) and humidity (not discussed here) throughout the PACK, located as shown in Figure 5-1. The aim of this experimental work is to support validation of SESAC and, in a step towards this, to support the verification of the PACK control system used in the simulation. The adopted scenarios used here represent: (i) a fault free, healthy run and: (ii) a faulty run, having an abrupt PACK shutdown due to a Ram air door failure.



Figure 5-2 Ground test facility of the Boeing 737-400, Left-side PACK data collection.

5.2 PACK Control System

The temperature demanded by the aircraft generally ranges between 18°C and 30°C [9]. The flight crew set the temperature demand using the temperature controls mounted on the P5 overhead panel in the cockpit. This information is then supplied to the PACK controller, which controls the operation of the PACK accordingly. Figure 5-3 shows the elements of the control system, comprising:

- i. The PV to control the bleed mass flow into the PACK.
- ii. The in-build thermal switches for PACK overheat protection.
- iii. The TCV and Ram air flow control to regulate the merge outlet temperature.

Each of these is described below, in this order.

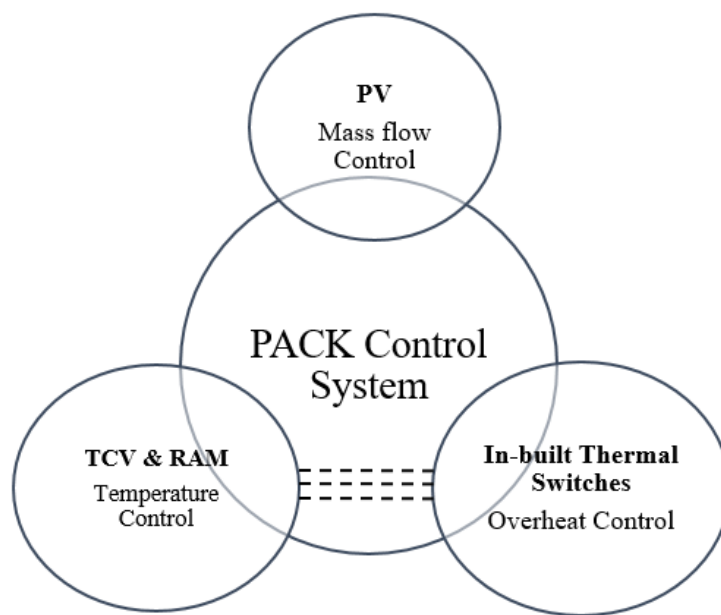


Figure 5-3 Overall elements of the PACK control system: overheat protection, temperature control and mass flow control.

5.2.1 Mass flow Control System

The PV is a butterfly valve with a venturi, a set of solenoids and air chambers, servo valve, total pressure sensing ports, pressure regulator, control orifice and a valve positioning indicator as shown in Figure 5-4. It is pneumatically controlled and actuated and responds to a number of inputs to effectively deliver a constant mass flow into the PACK. The servo valves are spring-loaded; opening and closing based on the pressure difference between the upstream, venturi, and downstream pressures. The air pressure in the chambers keeps adjusting until the desired mass flow through the valve is achieved. There are 2 different options available on the P5 overhead panel in the cockpit to run the pack – auto and high setting. While the auto setting is used for nominal operating condition, the high setting is used to power a single PACK in case of the other PACK failing. The high setting is also used on the ground, with single PACK operation, to achieve maximum cooling. As per the AMM [9], the overall PACK operation can be divided into two key operational states: (i) ground operation, and (ii) in-flight operation. During ground operations, since the aircraft main engines are switched off, the on-board auxiliary power unit supplies the bleed flow to the left PACK

only, which represents the maximum flow scenario compared to the in-flight scenarios. During in-flight conditions, the main engines provide the required bleed flow. In case of any in-flight PACK failure, the single PACK operation is maintained under high mass flow settings in order to maintain required cabin pressurisation and temperature. Under normal in-flight operation both PACK work in unison to supply the demanded cabin conditions. A qualitative view of this is presented in Fig. 4.

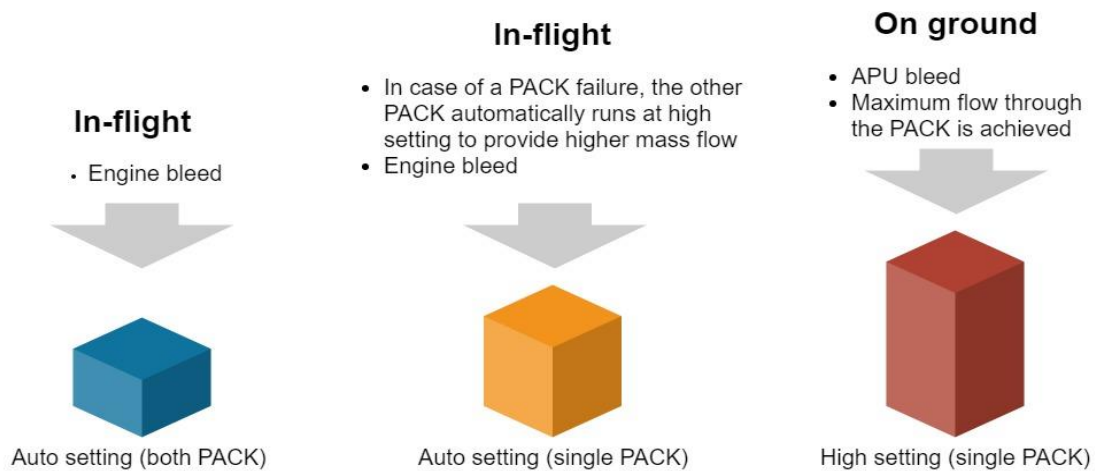


Figure 5-4 Illustration of the various PACK operational scenarios and their corresponding relative magnitude of mass flow.

The PV starts operating as the open-close solenoid C, shown in Figure 5-5, is energised retracting the ball valve actuator allowing controlled air flow through the control orifice to the actuator. This airflow is supplied by the upstream sense port. As the pressure in chamber A increases the actuator opens the butterfly valve and allows bleed air into the PACK. As mass flow through the valve increases the velocity of the airflow in the venturi and the upstream pressure increases. This results in pressure drop at chamber B and increase in pressure at chamber C and D. As the differential pressure in between chamber B and C increases the spring-loaded servo valve opens releasing pressure from chamber A. This moves the valve towards its closed position. This increase and decrease in pressure at chamber A continues until the valve reaches steady-state [9].

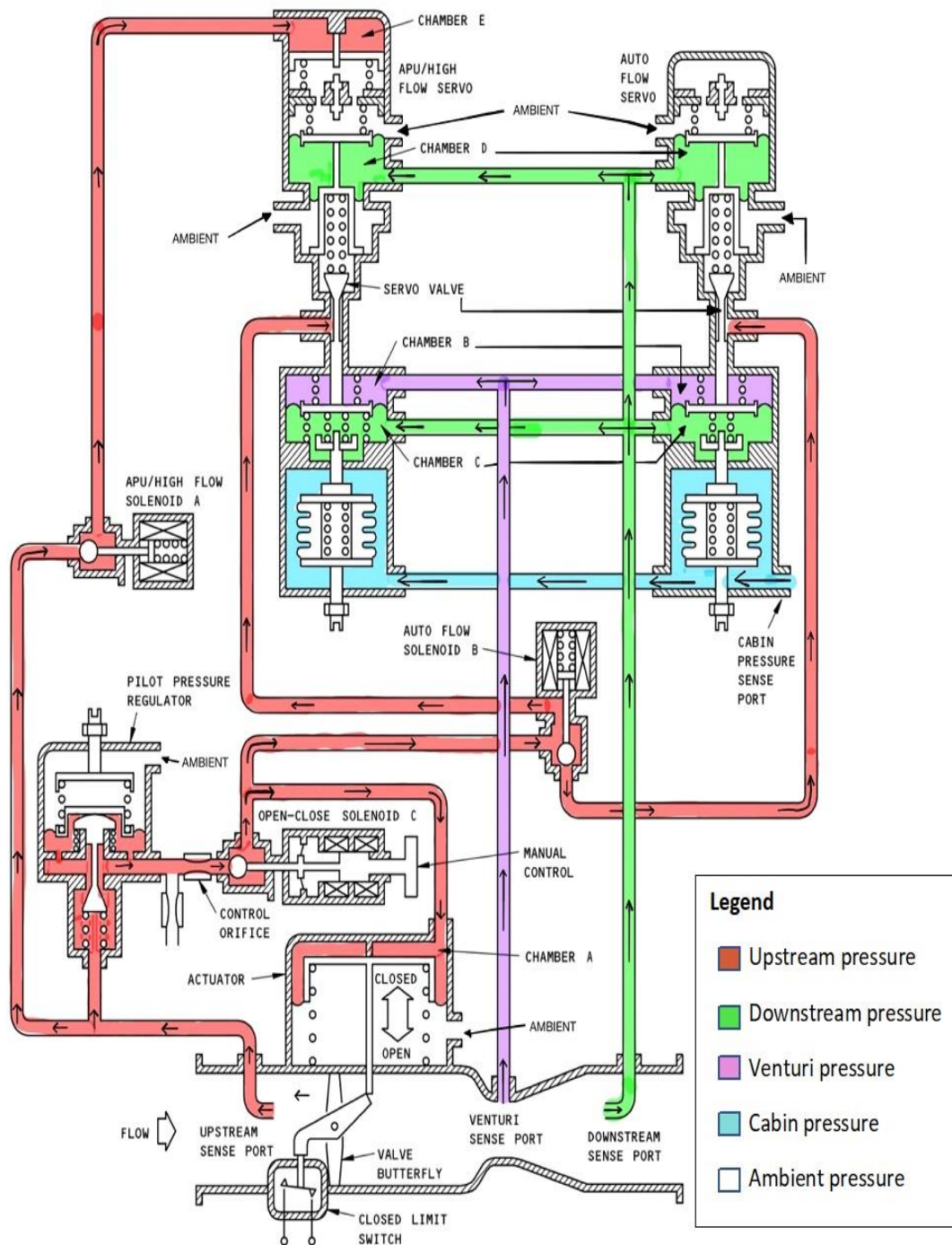


Figure 5-5 Schematic of the PV, adopted and reproduced from Boeing 737-400 AMM [9].

5.2.2 Overheat Protection

The PACK can experience overheat for a number of reasons. Generally, the PACK overheat can be caused due to: (i) malfunction of a component, e.g.

sticking of PV, TCV or of the Ram air modulating door, or: (ii) degradation of components, e.g. fouling or blockage of heat exchangers, or due to fouling or mechanical damage of the ACM. An aircraft incident occurred due to PV malfunction on a Boeing 737-700 flight to Melbourne in 2007 [10]. The aircraft experienced a failure of the right hand engine bleed during take-off. The flight was continued with only one PACK operational but, subsequently, during the climb to Flight level 350 (35000ft), the left air conditioning PACK valve malfunctioned. This resulted in the PACK shutting down and an emergency descent followed with passenger oxygen masks deploying as the cabin altitude exceeded 14000 feet [10].

To ensure the safety of the PACK system, three inbuilt thermal switches have been included in the PACK at different locations, as shown in Table 5-2. Each switch is prescribed with a temperature limit which, if exceeded, will activate the corresponding switch and the PACK controller will process the signal to immediately shut down the PACK by closing the PV.

Table 5-2 Locations of inbuilt thermal switches for overheat protection [9]

Inbuilt Thermal Switch	Location	Activation temperature limit
Compressor outlet overheat switch	Compressor outlet duct (CMP _o)	199°C
Turbine inlet overheat switch	Reheater outlet duct (RHX _{c,o})	99°C
PACK outlet overheat switch	Upstream of the check valve at the PACK outlet (PCK _o)	121°C

The Ram air inlet supplies the required cold mass flow for the primary (PHX) and secondary (SHX) cooling of the hot bleed air. In flight, air is readily captured from the aircraft's motion, but on the ground a small turbo-fan is used

to force air through the Ram duct. In case of the Ram air door or turbo-fan malfunctioning the amount of cold mass flow supplied to both the PHX and SHX is significantly influenced. Under these conditions, it has been established from previous studies reported by authors [1] that the increase in the PHX outlet temperature propagates through the compressor and results in an increased compressor outlet temperature, possibly triggering the compressor outlet overheat switch.

Figure 5-6(a) presents the test data for a healthy PACK run, having the Ram air door open and the turbo-fan running. The temperature readings at compressor outlet, turbine inlet and PACK outlet are shown against the test time. Both PHX and SHX are supplied with the required cold mass flow and therefore the temperatures approach a steady state value and remain below the thermal switch activation thresholds tabulated in Table 5-2. Figure 5-6(b) shows the case when the Ram turbo-fan malfunctions and both PHX and SHX receive no cooling flow. Here much hotter than intended air passes through the compressor and results in a dramatic increase in compressor outlet temperature, and activation of the compressor outlet thermal switch at 199 °C. In response, the control system immediately shuts the PACK valve in order to prevent overheating.

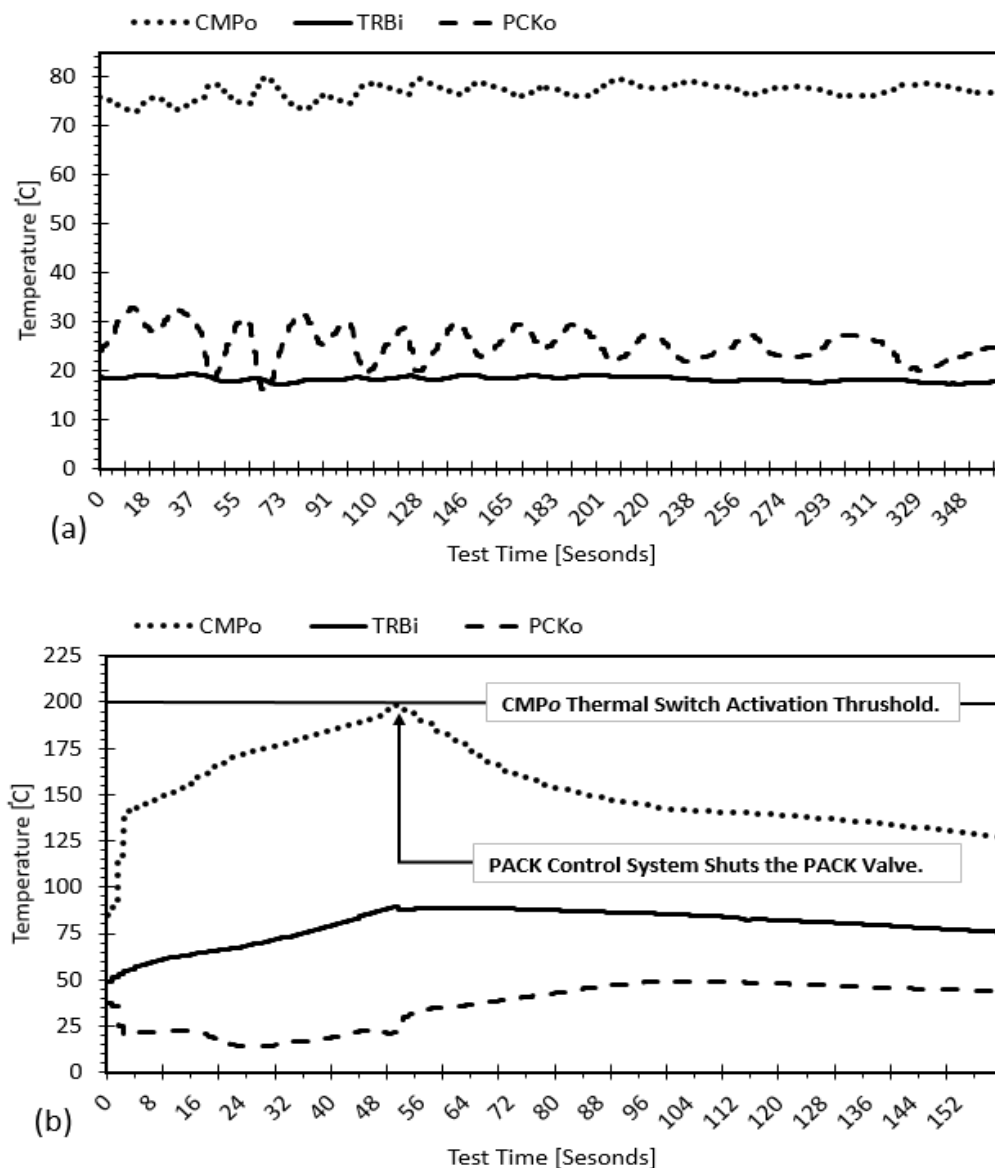


Figure 5-6 Compressor outlet thermal switch activation (a) data during ground run with the Ram turbofan switched on, (b) data during ground run with the Ram turbofan switched off.

5.2.3 Temperature Control System

5.2.3.1 Temperature Control valve

There are two TCVs in the PACK – a primary temperature control valve and a standby temperature control valve. The primary TCV is electrically controlled and mechanically actuated. The standby TCV is pneumatically and electrically controlled and pneumatically actuated. These valves are controlled through

sensing the WS outlet temperature. While both the TCVs regulate the PACK outlet temperature by varying bleed air into the turbine merge, the standby temperature control valve is only used to prevent ice formation at the turbine outlet.

Both the TCVs are butterfly valves. Based on the error between the demand and WS outlet temperature an electric motor drives a shaft rotating the butterfly valve to the desired opening. To enable this the sensor data is processed in the PACK control unit and the output signal controls the single-phase ac motor to achieve the lowest cabin demand at the PACK outlet. There are other sensors in the mixing manifold, and also inside the cabin, which are used to reach the desired cabin temperatures.

The standby TCV presented in Figure 5-7 provides two different functions: (i) de-icing and (ii) PACK outlet temperature control (when the primary TCV fails). In contrast to the PV, the stand-by TCV has two parts – pneumatic and electrical. The pneumatic side of the valve works similar to the PV. The chambers in the TCV detect pressure differential across the CHX and based on the valve upstream pressure it uses the pneumatic actuator to change the valve location. This part of the valve is used for de-icing in the condenser. There is also a dedicated chamber which has an electric torque motor and a flapper to isolate the pneumatic system and use ambient vent for opening or closing the valve using the pneumatic actuator.

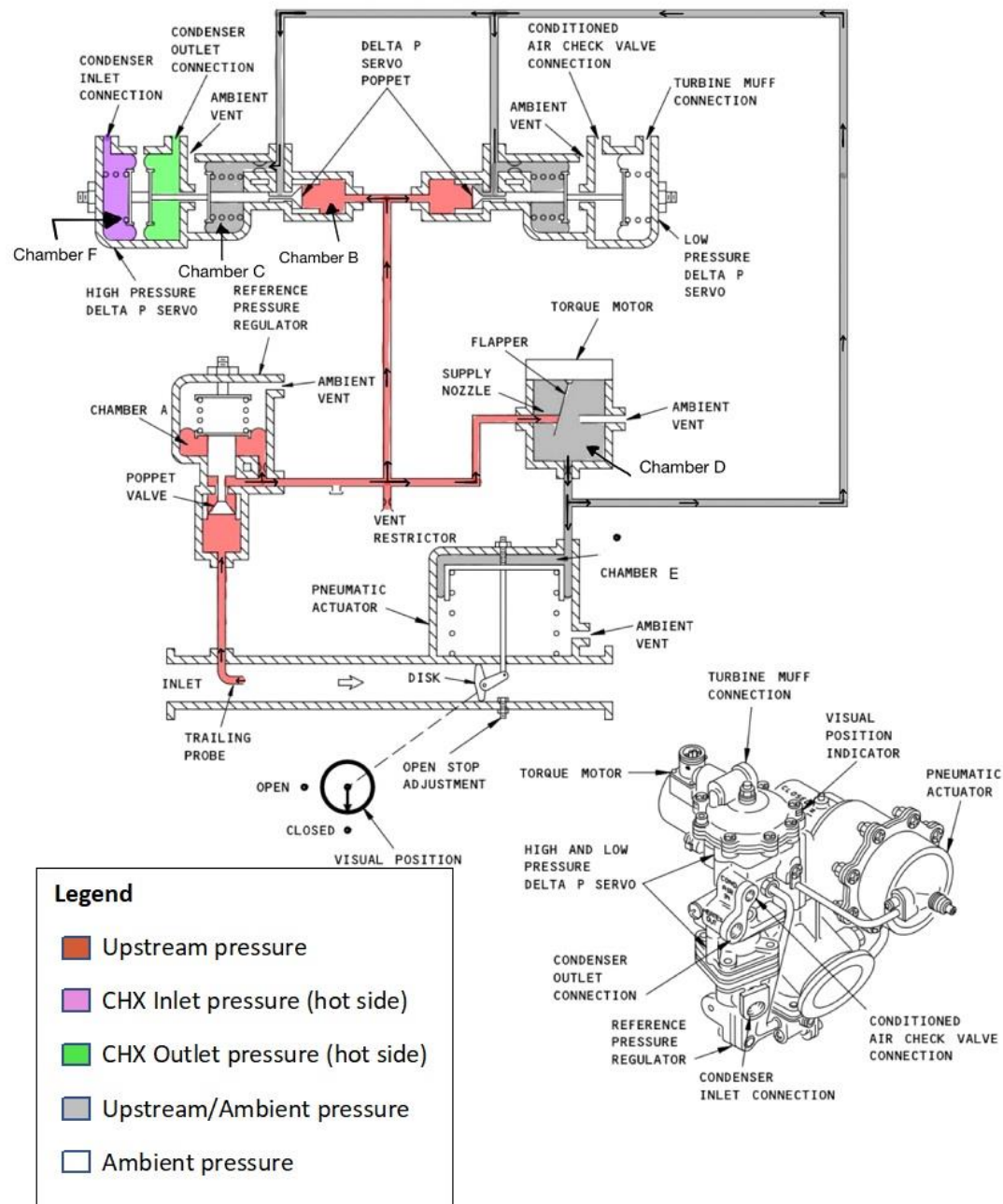


Figure 5-7 Standby temperature control valve, adopted and reproduced from Boeing 737-400 AMM [9].

5.2.3.2 Temperature Control Limits

The PACK temperature control primarily acts in two ways: (i) by controlling the cold Ram air supply by regulating the Ram air inlet modulating flap, and: (ii) by controlling the PACK outlet temperature through the hot bypass stream by regulating the TCV, see Figure 5-1.

It is necessary to regulate the PHX, SHX and turbine outlet temperature to meet the cabin demand using the temperature sensors listed in Table 5-3. These two inbuilt temperature sensors, at compressor outlet and water separator outlet, support the control system with necessary feedback to control the temperature throughout the PACK, and its compliance against the demanded cabin temperature. For the latter, the lowest temperature demand from the cabin is matched as the PACK outlet.

As previously discussed, during aircraft ground operation a small turbofan pulls in the air through the Ram air inlet. The Ram air inlet is maintained at maximum opening to ensure maximum possible air flow supply to the PHX and SHX.

When the aircraft is operated at altitude with flaps fully retracted, the mass flow that can be achieved through the Ram is dependent on the ambient conditions, as well as the flight Mach number. The PACK controller utilises the temperature sensor installed at the compressor outlet to control the supply of Ram air flow through the PHX and SHX in order to maintain the compressor outlet temperature to as near 110°C as possible. In cases where this temperature limit exceeds 110°C, the Ram door fully opens, allowing maximum possible mass flow, under this scenario the Ram door full open light will be on in the cockpit P5 overhead control panel. The overheat protection switch discussed in Section 2.2 will be triggered in case the compressor outlet temperature exceeds 199°C, and under this scenario the control system will shut down the PACK valve to prevent overheating.

Table 5-3 Inbuilt Temperature sensors for PACK temperature control.

Temperature Sensor	Location	Threshold
Ram air temperature sensor	Compressor outlet duct (CMP _o)	Regulates Ram mass flow maintain the Compressor outlet temperature to as near 110 °C as possible
PACK temperature sensor	Water extractor outlet duct (WS _o)	Regulates TCV opening to maintain the lowest temperature demand from the zone

To regulate the PACK outlet temperature, the TCV is set to mix hot bleed air with the cold air coming out of the turbine. The temperature controller processes the sensor signal from the WS outlet duct, which is then used to open or close the TCV, to match the cabin temperature demand. A healthy ground run experiment, with a cabin temperature demand set at auto settings (which represents around 24 °C), is shown in Figure 5-8. Both the WS outlet and the PACK outlet temperatures approach steady-state at an average of 22°C. Note that the target temperature for the WS outlet is set to maintain the lowest cabin demand at the PACK outlet. As the TCV is working continuously to maintain a constant temperature at the WS outlet by mixing hot air at the merge, the PACK outlet temperature can oscillate, and can be different from the lowest cabin demand. The air distribution system, which includes a mixing manifold, the trim system, and the recirculation system, will then regulate air supply to each cabin zone to match their individual temperature demands.

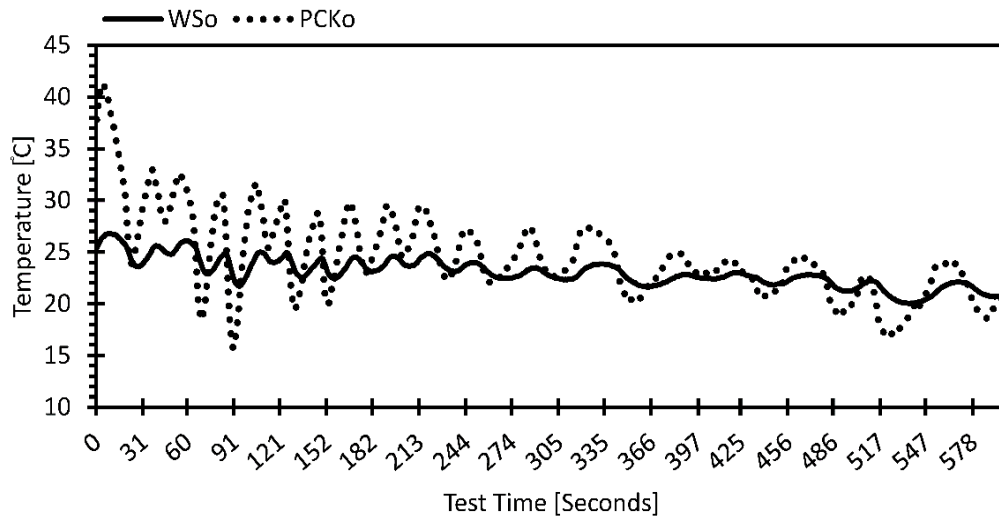


Figure 5-8 Experimental data, WS outlet and PACK outlet temperature.

5.3 PACK Simulation Model and Controller

5.3.1 PACK Simulation Model

Figure 5-9 presents the B737 PACK model based on the SESAC library. The model configuration in terms of the architecture and flow sequence naturally mirrors the B737 schematic presented in Figure 5-1. The PACK receives input bleed air at high temperature and pressure from the engine or APU. It conditions this air to meet requirements from the cabin. The addition in Figure 5-9 is the two feedback loops, one for temperature and one for mass flow. The temperature loop monitors, via a virtual sensor, the merge outlet temperature and controls it by adjusting the amount of hot air admitted to the merge by the TCV. The mass flow loop begins with a virtual sensor at the PACK exit and feeds back to the PACK valve to control the flow against a target value.

The simulation framework SESAC employed within the chapter has been verified and validated (V&V) against the data provided by the sponsors. The overall computational development of the framework and its V&V is reported by Jennions et al. in reference [7].

5.3.2 Boundary Conditions

In order to simulate the performance characteristics of the PACK, under given aircraft operating conditions, boundary conditions for the PACK must be defined. These can be categorised in four parts, as shown in

Table 5-4: (i) Aircraft state condition. This allows the model to determine the Ram mass flow, which serves as the input to the PHX and SHX cold streams. The Ram mass flow is determined based on the aircraft operating conditions, i.e. Mach number, ambient conditions, and Ram intake geometry. (ii) Bleed air properties, in terms of T, P, specific humidity, and water content are required. (iii) Target outlet conditions, i.e. T, P, and $\dot{m}$. (iv) Component health state, represented by the degradation severity (DS) which varies from 0 (healthy) to 100 (fully degraded) [7].

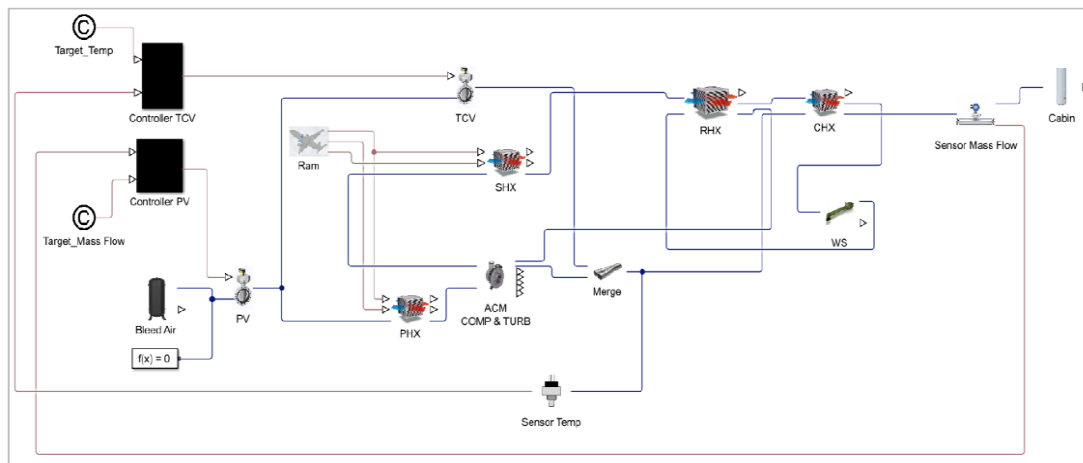


Figure 5-9 SESAC PACK simulation model for Boeing 737-400, model mirrors the schematic presented in Figure 5-1 [7].

Table 5-4 SESAC PACK simulation model boundary conditions [7].

Component	Parameters	Description	Units
Aircraft State condition	Selector (S)	Determines if the aircraft is in flight or operating at ground static conditions. 1= inflight, 0 = ground static.	(-)
Ram (0: Ground Static)	$\dot{m}$	Ram $\dot{m}$ is required if aircraft operating at ground static.	(-)
	T_{amb}	Ambient temperature	(K)
Ram (1: In flight)	Alt	Aircraft Altitude	(m)
	Mach	Aircraft Mach number	(-)
	Area	Ram door total area	(m ²)
	%Open	Ram door opening in %	(%)
Bleed Air properties	$PV_i - T$	Inlet temperature to PV	(K)
	$PV_i - P$	Inlet pressure to PV	(Pa)
	$PV_i - SH$	Inlet specific humidity at PV	(kg/k)
	$PV_i - CO$	Inlet liquid water content at PV	(kg/k)
Target Conditions	P_{target}	Target pressure	(Pa)
	T_{target}	Target temperature	(K)
	$\dot{m}_{target}$	Target mass flow	(kg/s)
Component health state	DS	Degradation severity level	(%)

5.3.3 Controller for the PACK Simulation

The PACK fundamentally achieves the temperature control through the TCV and regulates the mass flow through the pneumatic PV system. To ensure that the target mass flow at the PACK outlet is attained, an appropriate control is required to regulate the PV. Similarly, a separate controller is required for regulating the TCV to achieve the target temperature, as shown in Figure 5-9. From the Simscape library, the integral controller was selected for the control of the PV and TCV. The schematic of the implemented PV and TCV integral controller are

shown in Figure 5-10. The controller receives a signal from the virtual sensor and calculates the error relative to the target value. A gain is used to amplify the error which is then provided as an input to the integral block. The physical signal (PS) integrator block outputs the integral of its input at the current time step. The integral block requires an initial condition in order to determine the initial state at the beginning of a simulation run (e.g. at time = 0). The following equation represents the output of the integral block for the PV [11]:

$$Y_{(t)} = \int_{t_0}^{t=1} u(t)dt + y_0 \quad (5-1)$$

Where, in the case of mass flow control:

u	Amplified mass flow error
Y	Output PV angle
y ₀	Initial condition for PV angle
t	Simulation time

Where:

$$\text{Error} = \frac{T_{in} - \text{Sensor}_{in}}{T_{in}} \quad (5-2)$$

The solver computes the output of the integrator block at the current time step, using the current input value and the value of the state at the previous time step. To support this, the integrator block saves its output at the current time step for use by the solver to compute its output at the next time step. Iteratively, the integrator block will continue to perform the computations until the error is zero [12].

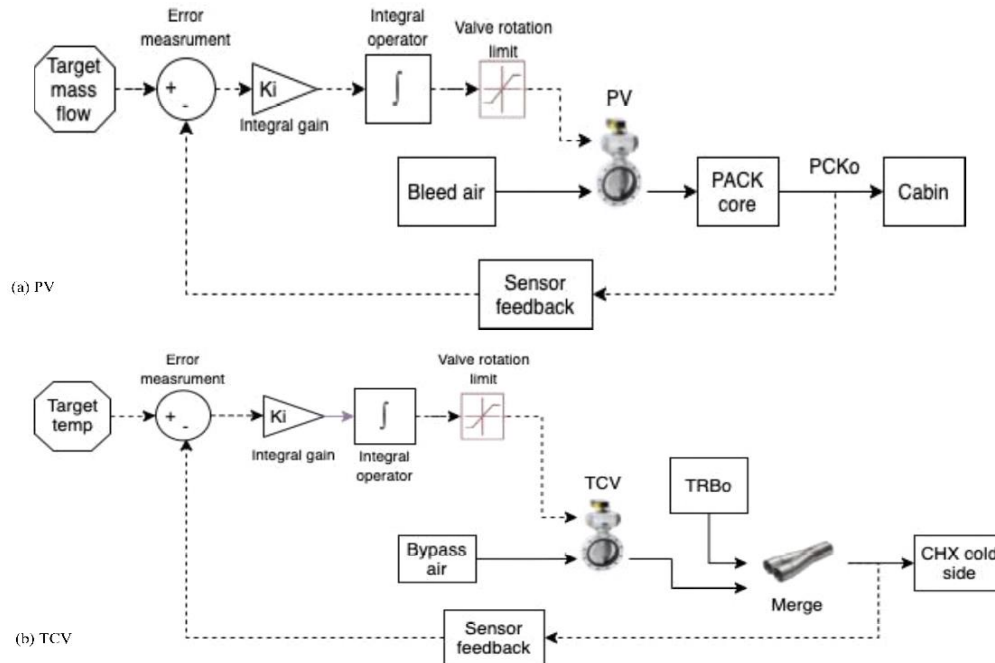
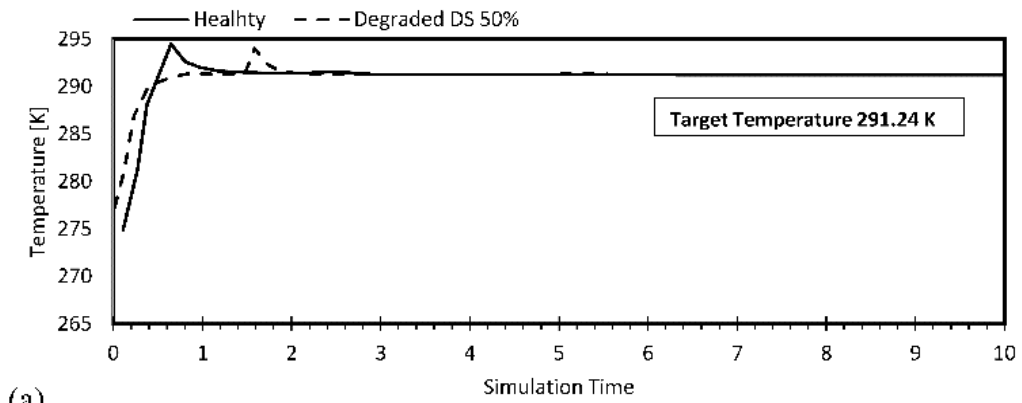
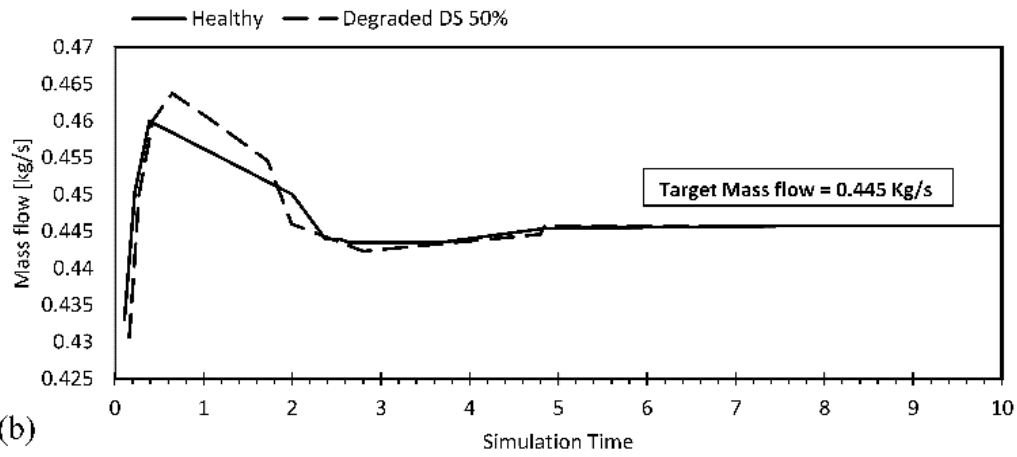


Figure 5-10 Implemented PS integrator controller for the PV and TCV control in the SESAC PACK model.

Figure 5-11 presents the response of the integral controller when simulated for healthy and faulty conditions. The faulty condition represents a 50% degradation in the PACK PHX. It can be observed that the response of the controller is robust and time efficient. In both cases, an overshoot can be observed which can be attributed to the initial condition provided to the integrator in terms of the valve angle. For example, in the case of the mass flow, the provided initial condition of the PV angle leads to a higher mass flow than the target, hence the overshoot. The controller therefore reduces the angle through the iterative process in order to match the mass flow. The model presented in Figure 5-9 with the integral controller for PV and TCV can now be implemented for the assessment of fault simulation of the PACK at component level.



(a)



(b)

Figure 5-11 The implemented integral controller response for temperature and mass flow.

5.4 Results & Discussion

This section is presented in two main parts. In the first part, the PACK performance characteristics in terms of temperature, pressure and mass flow are presented for two reference aircraft cruise operating conditions. Degradation in the PHX is simulated under both conditions, this is done with the view to assess the robustness of the model under varying boundary conditions, and to substantiate the importance of employing systematically derived control logic to enable accurate fault simulation. In the second part, model simulations are conducted to simulate malfunction in the PV and TCV, and their impact on the PACK performance characteristics is discussed.

5.4.1 Integral Controller-Based PACK Fault Simulation

Table 5-5 presents the two reference cruise operating points considered for the demonstration of the PACK fault simulation. The developed SESAC simulation model presented in Figure 5-9 was implemented to simulate the degradation in the PHX at various degradation severity levels for both references cases. The PACK boundary conditions for both reference cases were provided by the project industrial partner. In Table 5-5 the inlet, and the outlet target boundary conditions are provided in terms of the PACK inlet pressure, PACK outlet mass flow and the temperature (i.e. target mass flow and temperature). During cruise, the bleed air is extracted from the main engines high pressure compressor, and generally multiple bleed extraction stations are included in order to extract bleed flow at different levels of pressure. It can be observed from Table 5-5 that, as the aircraft altitude increases from 30000ft to 35000ft between RC1 and RC2. The higher RC2 altitude, having lower outside temperature relative to RC1, considering the heat balance over the aircraft, the cabin temperature demand will rise, therefore demanding relatively cooler flow. To allow the PACK to deliver cooler air flow, the bleed pressure ($PV_i - P$) is increased so that the air is supplied to the PACK at higher pressure to allow higher expansion through the ACM turbine.

Table 5-5 Reference cases implemented for fault simulation.

Reference Case	Altitude	PVIP	$\dot{m}_{\text{target}}$ (kg/s)	T_{target} (K)
1	30000 ft	191 kPa	0.4434	295.54
2	35000 ft	230 kPa	0.4234	284.42

5.4.1.1 RC1 PHX Degradation

Figure 5-12 presents the simulation results under PHX degradation for RC1. For the degradation of the PHX, the blockage in the PHX cold side intake is considered. The sticking of relatively large dust particles, debris and/or random foreign objects (e.g. a bird), ingested from outside the aircraft through the Ram air intake, cause heat exchanger degradation due to blockage. This flow is not filtered before it is supplied to the PHX, and therefore there is a risk of large dust particles or foreign objects passing through the Ram air intake.

Blockage in the PHX cold side inlet will cause a drop in PHX effectiveness. To simulate the blockage, the PHX effectiveness value acquired under healthy conditions was gradually degraded (at 10% intervals) in order to simulate various severity levels (e.g. a 10% degradation translates to 10% reduction in the PHX healthy effectiveness value). The reduction in the PHX effectiveness consequently reduces the heat transfer through the PHX and increases its outlet temperature as presented in Figure 5-12(a). The PHX and SHX are identical units in terms of their design, size, and shape. The large temperature difference at PHX outlet is carried through the compressor unchanged and then the SHX removes most of the excess heat, its outlet temperature only changing slightly. Effectively the PHX and SHX are acting together as one large heat exchanger (Figure 5-1), both using the Ram air to cool the main flow. They each receive 50% of the Ram air but the SHX can use it more efficiently than the degraded PHX. The entire temperature deficit is not recovered due to the cold Ram flow to the SHX being limited. This results in the overall effect of the PHX fouling on the turbine outlet temperature being minimal.

Due to the increased temperature at the merge, the TCV gradually shuts to allow more mass flow through the turbine in order to achieve maximum expansion and cooling efficiency. The closure of the TCV creates a back pressure on the PV outlet, creating a reduction in pressure across the PV (Figure 5-12b). As the pressure differential across the valve decreases, the mass flow drops. With increasing level of degradation, the mass flow controller opens the PV, as shown in Figure 5-13, in order to attempt to match the target mass flow. Until the point where the PV is fully open and cannot deliver any more flow. At this point, under further degradation, the PACK inlet mass flow decreases in order to satisfy the merge conditions, given the PV cannot open any more. The PV saturates at 90% degradation, which corresponds to the maximum back pressure on PV, as the $P_{V_o} - P$ approaches $P_{V_i} - P$ (Figure 5-13), resulting in a marginal drop in PV inlet mass flow (Figure 5-13c).

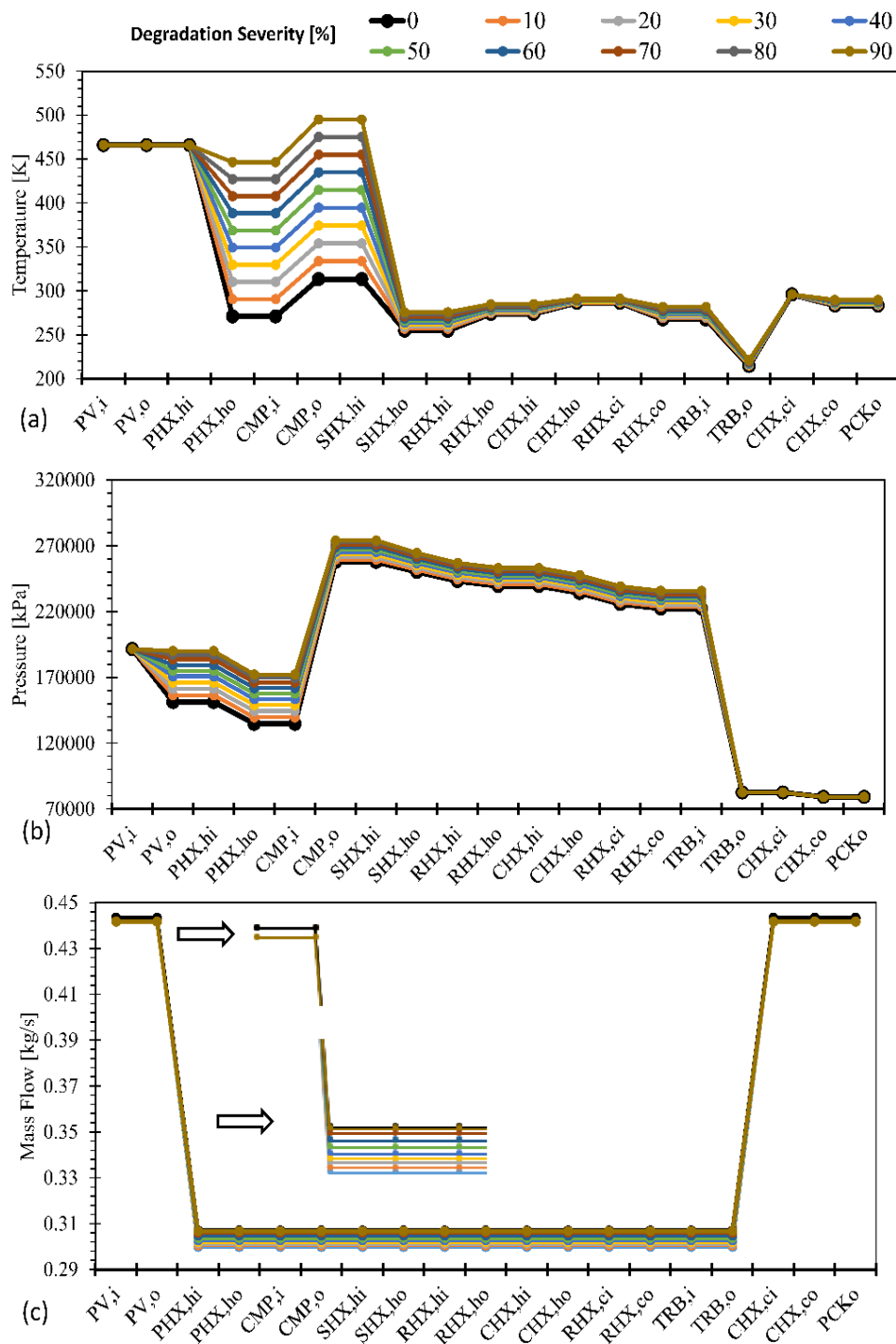


Figure 5-12 PHX degradation simulation results for RC1.

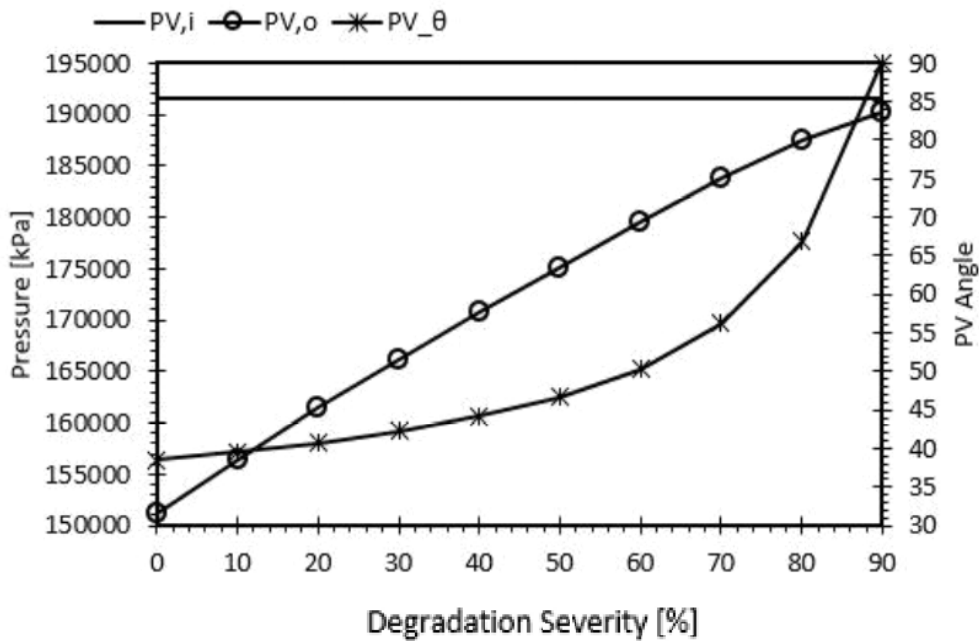


Figure 5-13 Variation in PVIP, PVOP, and PV angles, PHX degradation simulation results for RC1.

5.4.1.2 RC2 PHX Degradation

The simulation results for the PACK performance characteristics under PHX degradation are presented in Figure 5-14 for RC2. It is evident from Figure 5-14 that the performance characteristics remain similar to RC1, except the mass flow. In terms of the mass flow it can be observed that, relative to the RC1, the mass flow at the PV inlet remains constant for all the degraded cases, despite the presence of back pressure on the PV. The PV is able to maintain the target mass flow against the imposed back pressure caused due to the closure of the TCV. This stems from the fact that even in the worse degraded scenario the PVOP remains substantially lower than the $PV_i - P$ (Figure 5-15b), resulting in sufficient pressure drop across the PV to maintain target mass flow. The PV under these conditions is only required to marginally adjust its opening to match the target mass flow as shown in Figure 5-15(c). Based on the results acquired for both RCs, it can be claimed that the proposed PACK control logic in section 5.3.3 enables the acquisition of accurate engineering design and physics of the PACK both under healthy and degraded functional scenarios. The model can now be further used to assess malfunction in PV and TCV.

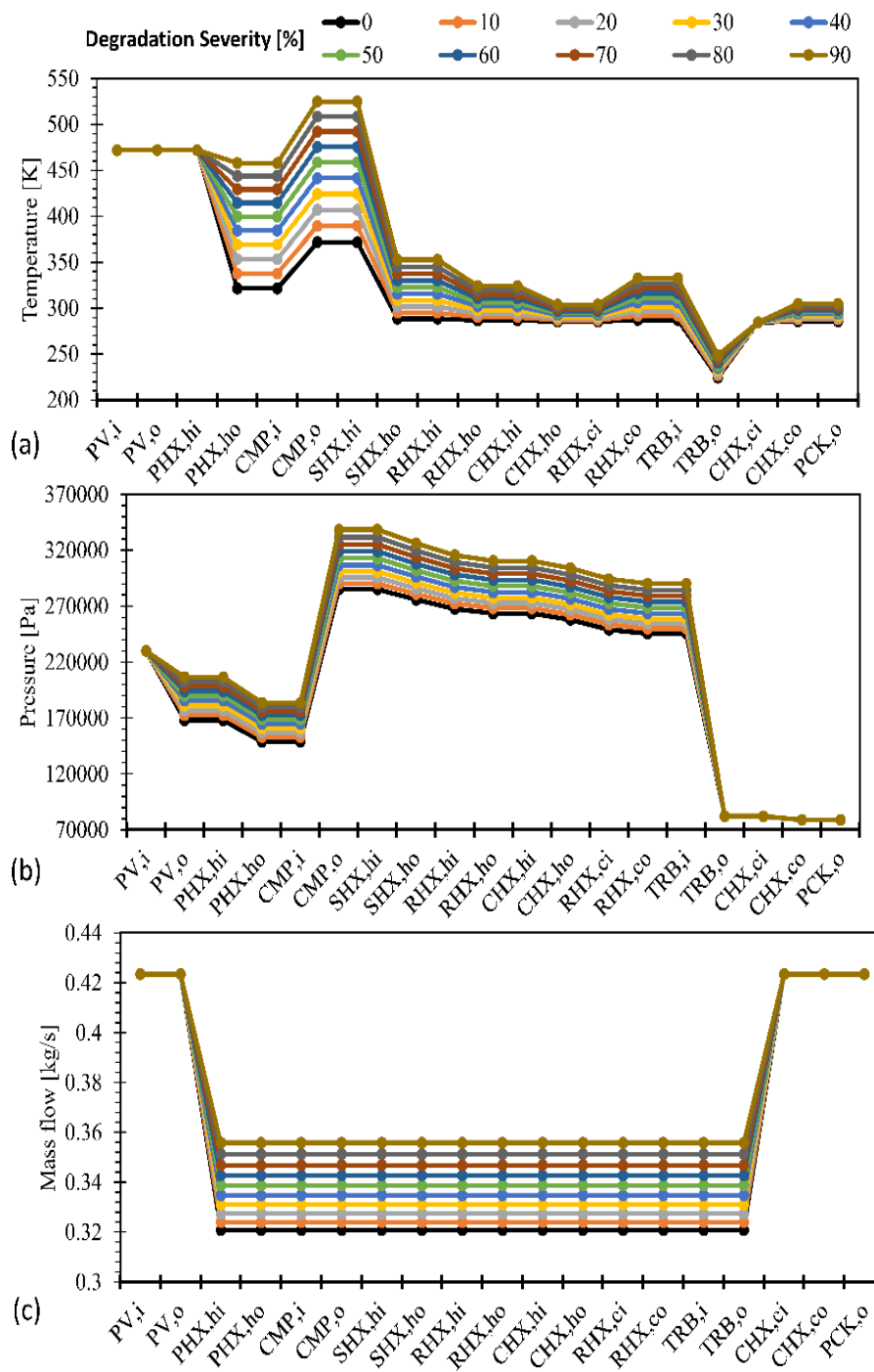


Figure 5-14 PHX degradation simulation results for RC2.

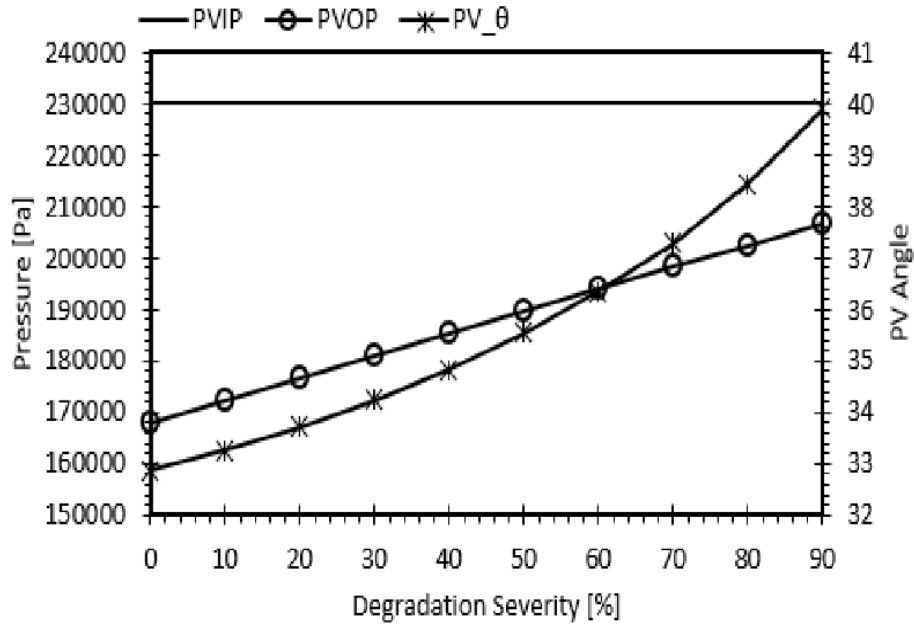


Figure 5-15 Variation in PVIP, PVOP, and PV angles, PHX degradation simulation results for RC2.

5.4.2 Malfunction of Control Valves

This section presents the results acquired based on the simulation of PV and TCV malfunction for RC1. The malfunction for PV and TCV is simulated by overshooting or undershooting the valve angle from the healthy baseline valve angle presented in Table 5-6. The impact of PV and TCV valve malfunction on the performance characteristics of the PACK is presented at various severities.

5.4.2.1 PV Malfunction

Table 5-6 presents the percentage overshoot and undershoot of the PV relative to the baseline healthy valve angle. The simulations are conducted by changing the PV controller saturation limit to the corresponding values of the overshoot/undershoot, while making no changes to the TCV controller. The acquired results in terms of temperature, pressure and mass flow are presented in Figure 5-16. As shown in Figure 5-16 (c), the overshoot of the PV results in increased mass flow through the PV. This is to be expected as the PV opening increases, reducing the pressure drop across the PV and allowing more mass flow. The increased mass flow through the core of the PACK increases the expansion through the turbine, resulting in colder turbine outlet temperature

relative to the baseline, as shown in Figure 5-16 (a). Under these conditions, the TCV is required to increase the supply of hot mass flow in order to match the target temperature. As tabulated in Table 5-6, the TCV valve opening increases with increase in the severity of the overshoot.

Interestingly, as highlighted in Figure 5-16 (a), the PHX outlet temperature increases as a result of the PV overshoot. This can be attributed to the fact that, as more hot mass flow is fed through the hot side of the PHX, the Ram mass flow on the PHX cold side remains unchanged. Therefore, the heat transfer across the PHX drops, which results in the increased PHX outlet temperature.

With regards to the undershoot of the PV, exactly the opposite response in the PACK performance characteristics can be observed. The closing of the PV results in reduced overall mass flow relative to the healthy case, this reduces the mass flow through the core, which reduces the expansion through the turbine, resulting in warmer turbine outlet temperature relative to the healthy case. The TCV must close in order to reduce the hot mass flow to match target temperature.

Table 5-6 TCV variation with PV malfunction.

% PV Overshoot/undershoot	PV Angle (°)	TCV Angle (°)
40	56.0	22.5
30	52.0	22.2
20	48.0	21.9
Healthy	40.0	20.4
-20	32.0	18.9
-30	28.0	17.6
-40	24.0	15.7

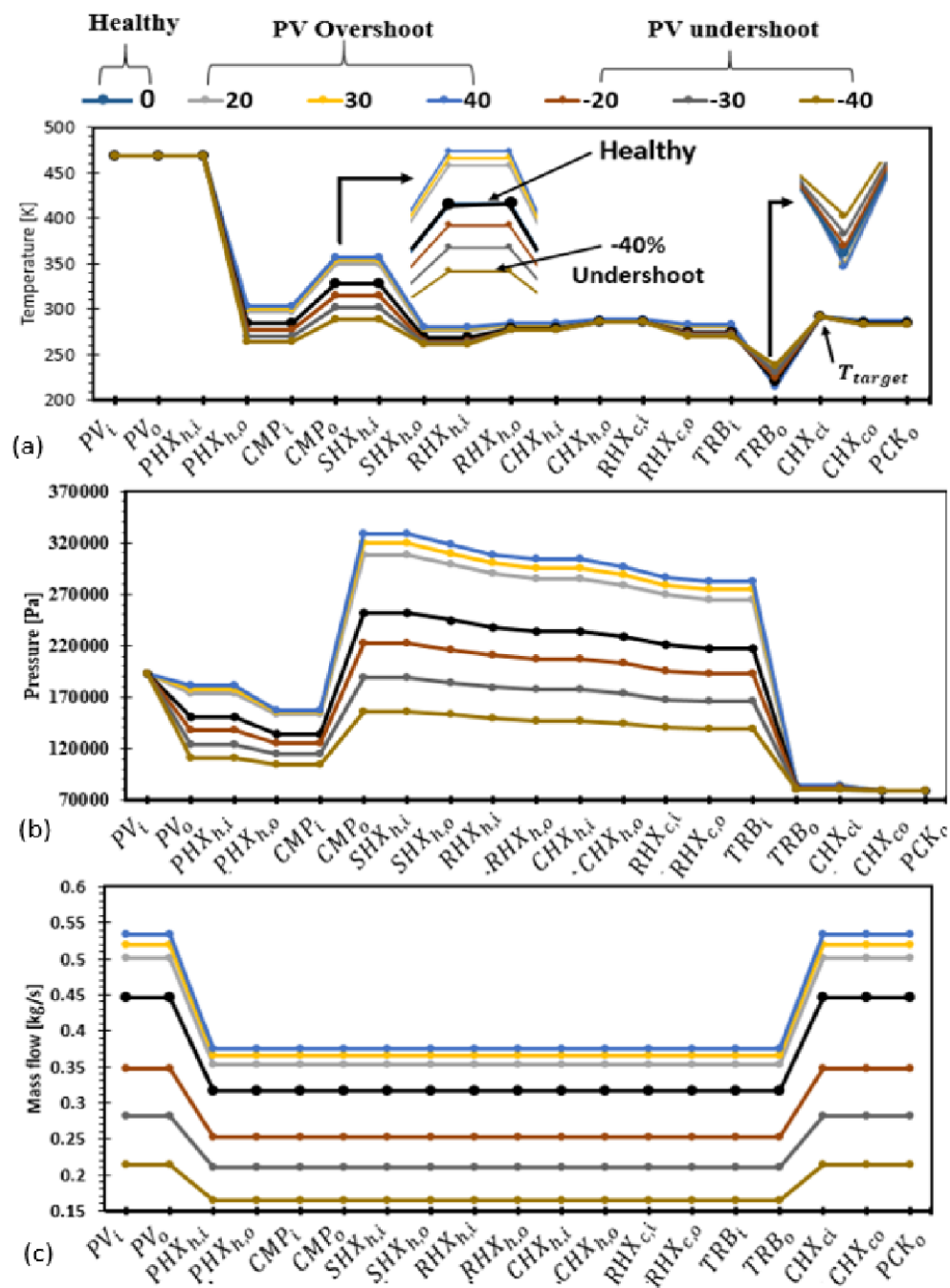


Figure 5-16 : Simulation results for PACK performance characteristics under PV malfunction.

5.4.2.2 TCV Malfunction

Table 5-7 presents the percentage overshoot and undershoot of the TCV, relative to the baseline healthy valve angle of RC1. The simulations are conducted by changing the TCV controller saturation limit to the corresponding value of the overshoot/undershoot, while making no changes to the PV controller. The acquired results in terms of temperature, pressure and mass flow are presented in Figure 5-17. In the case of overshoot, the increase in TCV opening relative to the healthy case will alleviate the back pressure from the PV, which will increase the pressure drop across it, resulting in reduced PACK inlet mass flow. In this scenario, relative to baseline the core mass flow drops which consequently results in warmer turbine outlet temperature, as the expansion through the turbine reduces compared to baseline. With the TCV being stuck at increased opening angle, the hot mass flow through the TCV increases, as a result the temperature at the merge outlet overshoots the target temperature. It can be said that, in a scenario where the TCV overshoot severity increases well beyond 30%, the PACK outlet overheat thermal switch (see, Section 5.2.1, Table 5-2) which has an activation threshold of (121°C/394 K) will be activated, and the PACK control system will shut down the PV to prevent overheating. Lastly, due to the drop in core mass flow, while cold mass flow through the Ram remains unchanged, resulting in improved heat transfer across the PHX relative to healthy case.

In terms of the TCV undershoot, which represents the closing of the TCV relative to the healthy case, due to the closing of the TCV, the back pressure on the PV increases, reducing pressure drop across PV, against this back pressure, PV opening increases, and so does the mass flow through the core. Due to increased core mass flow, and turbine expansion, colder turbine outlet temperature results when compared to the healthy case. As the TCV is undershooting and is stuck, this leads to the lack of sufficient hot mass flow supply through the TCV, and as a consequence the merge outlet temperature undershoots the target temperature. For a fixed cold Ram mass flow, the increased core mass flow also has a detrimental impact on heat transfer through the PHX.

Table 5-7 Variation in PACK performance characteristics parameters under TCV malfunction.

% TCV Overshoot/undershoot	PV Angle (°)	TCV Angle (°)
30	36.9	26.4
20	37.8	24.4
10	39.0	22.4
Healthy	40.0	20.4
-10	43.6	18.4
-20	47.1	16.4
-30	50.2	14.4

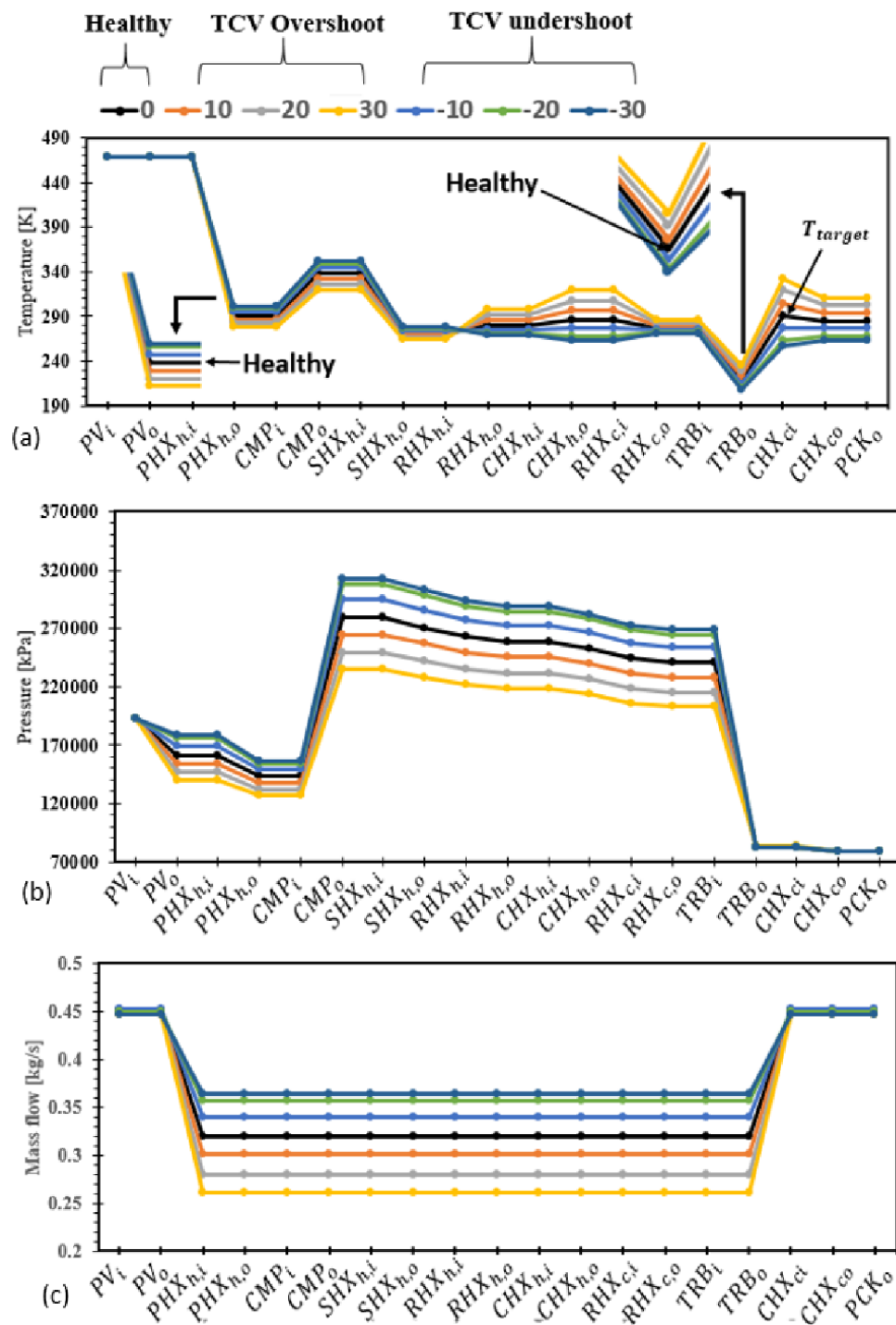


Figure 5-17 Simulation results for PACK performance characteristics under TCV malfunction at various severities.

5.5 Conclusions

In this chapter, the overall control system of the B737-400 PACK has been investigated in order to support the implementation of an accurate simulation model for fault diagnostics. The PACK control system elements, i.e. mass flow and temperature control valves, Ram flow control, and overheat protection control system, are discussed and their operation is verified against the actual data acquired from the Cranfield B737-400 aircraft.

Based on the assessment and understanding of the PACK in-situ control system improvements in the previously employed PACK control system are proposed for accurate fault simulation. An integral controller for the control of the TCV and PV are proposed, and implemented to simulate PHX degradation at various severity levels at two reference aircraft cruise conditions. Based on the acquired results it was verified that the proposed control logic accurately captures the engineering and physics of the PACK under both health and degraded functional scenarios. Finally, the simulations were further exercised to assess the malfunction in the TCV and PV at various severities. The impact of TCV and PV malfunction on the PACK performance characteristics in terms of temperature, pressure and mass flow was presented and discussed.

The B737-400 PACK simulation proposed in this chapter enables the accurate fault simulation of the sub-systems at various degradation severities, which serves as a foundation for formulating accurate diagnostics. The developed model application will be further extended to produce a robust diagnostics solution for an aircraft PACK.

References

1. Jennions I., Ali F. Assessment of Heat Exchanger Degradation in a Boeing 737-800 Environmental Control System. *Journal of Thermal Science and Engineering Applications*. 1 December 2021; 13(6). Available at: DOI:10.1115/1.4050324
2. Esperon-Miguez M., Jennions IK., Escobar IC., Hanov N. Simulating faults in a Boeing 737-200 Environmental Control System using a thermodynamic

- model. *International Journal of Prognostics and Health Management*. 1 June 2019; 10(2): 1–12. Available at: DOI:10.36001/ijphm.2019.v10i2.2731
3. Esperon-Miguez M., John P., Jennions IK. A review of Integrated Vehicle Health Management tools for legacy platforms: Challenges and opportunities. *Progress in Aerospace Sciences*. Elsevier; 2013; 56: 19–34. Available at: DOI:10.1016/j.paerosci.2012.04.003
 4. Ezhilarasu CM., Skaf Z., Jennions IK. A Generalised Methodology for the Diagnosis of Aircraft Systems. *IEEE Access*. 2021; 9: 11437–11454. Available at: DOI:10.1109/ACCESS.2021.3050877
 5. Ezhilarasu CM., Skaf Z., Jennions IK. Progress in Aerospace Sciences The application of reasoning to aerospace Integrated Vehicle Health Management (IVHM): Challenges and opportunities. *Progress in Aerospace Sciences*. Elsevier Ltd; 2019; 105(December 2018): 60–73. Available at: DOI:10.1016/j.paerosci.2019.01.001
 6. Ezhilarasu CM., Jennions IK. A System-Level Failure Propagation Detectability Using ANFIS for an Aircraft Electrical Power System. *Applied Sciences*. 20 April 2020; 10(8): 2854. Available at: DOI:10.3390/app10082854
 7. Jennions I., Ali F., Miguez ME., Escobar IC. Simulation of an aircraft environmental control system. *Applied Thermal Engineering*. May 2020; 172: 114925. Available at: DOI:10.1016/j.applthermaleng.2020.114925
 8. Chowdhury S., Ali F., Jennions I. A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics. *Proceedings of the Annual Conference of the PHM Society* 2019. 2019. pp. 1–11. Available at: DOI:https://doi.org/10.36001/phmconf.2019.v11i1.888
 9. Boeing 737-300/400/500 Aircraft Maintenance Manual, D6-3758.
 10. Skybrary. B737 en-route, Glen Innes NSW Australia, 2007. 2017. Available

at: https://www.skybrary.aero/index.php/B737_en-route,_Glen_Innes_NSW_Australia,_2007 (Accessed: 26 June 2019)

11. Mathworks. Integrator Limited. Available at: <https://uk.mathworks.com/help/simulink/slref/integratorlimited.html?nocookie=true> (Accessed: 20 April 2022)
12. Mathworks. PS Integrator. Available at: https://kr.mathworks.com/help/physmod/simscape/ref/psintegrator.html?nocookie=true&s_tid=gn_loc_drop (Accessed: 20 April 2022)

6 Summary and Future Works

‘However life may seem, there is always something you can do and succeed at.’

- Stephen Hawking

This chapter summarises the key findings and highlights the contributions made within this PhD. It concludes with a discussion on the potential areas for future work associated with the 737 Ground Test Facility (GTF) developed during this research.

6.1 Thesis Summary

Ensuring safety of the aircraft is the primary concern for both the manufacturers and airlines. The routine maintenance of key systems of the aircraft to prevent accidents or unplanned downtime is seen to increase the maintenance costs to billions of US dollars per year [1]. The Boeing Company, funding body of this study, has reported the aircraft Environmental Control System (ECS) of the legacy aircraft Boeing 737 to be a major driver for maintenance [2]. A number of incidents associated to the B737 ECS has also been highlighted in chapter 1 and 2 [3–6], regarding abrupt cabin pressure loss due to ECS failure. Researchers in the past have focused on developing diagnostic methods dedicated towards the ECS system. To contribute to the field of ECS diagnostics, the aim of this PhD research was to conduct a comprehensive experimental investigation of a Boeing 737-400 ECS including humidity and to use the experimental data to compare against the IVHM Centre’s in-house model-based simulation platform, SESAC.

A methodological approach highlighting the aim and objectives of this PhD was published in the Annual Conference of the Prognostics and Health Management Society 2019 [7]. The objectives and potential contribution sectors evolved with the progression of the PhD and was highlighted in Chapter 1. The methodology consists of 4 phases: Literature review, Experimentation, Simulation V&V, Humidity analysis and Thesis. Through these phases, 4

contribution sectors were set for this PhD C1-C5. Following are the summary of the contributions made through this PhD research.

6.1.1 Contribution 1

A literature review on the diagnostic methodologies that can be applicable to the ECS is presented in Chapter 2. This chapter is currently in the process of submission to a journal for publication. Following are the summary of the findings made from the literature review:

- i. It has been found that the diagnostic work in the past has mostly focused on the heat exchanger degradation. Model-based approach has been seen to be widely used in the context of heat exchanger degradation studies and it is primarily due to scarcity of data available from aircraft. A taxonomy of different diagnostic methods available is presented in Chapter 2.
- ii. Although one of the key functionalities of the ECS is to regulate humidity, the failure mode and diagnostic study for the High Pressure Water Separator (HPWS) is missing from the open literature.
- iii. The ECS consists of multiple subsystems and the mass flow around the system is regulated by dedicated control logic and valves. These valves have the capability to mask any fault occurrences. In addition to that, in an integrated system like ECS the fault can propagate through the system, making the diagnostic activity very difficult. Analysing ECS at a system level provides knowledge of component interdependencies for which system-level simulation models are required. It has been found that the simulation model discussed in the past were primarily developed and used for design purposes, except for SESAC. SESAC has the capability to perform comprehensive healthy and degraded simulation studies.
- iv. The system-level simulation study on the ECS fault occurrence and the model-based diagnostic methodologies are dependent on the accuracy of the model, therefore, a comprehensive V&V of the model to be used is crucial. In the past there has been a few experimental investigations conducted on the ECS, but they were on the ECS with Low Pressure

Water Separator System and the data collected was largely based only on the temperature readings. Therefore, a need for a 737 GTF on a civil aircraft ECS PACK with a HPWS system is deemed necessary.

- v. As highlighted earlier, the control system and the valves regulating the flow within the ECS to meet target conditions have potential to mask any fault occurrences. From the literature review it has been identified that there is a lack of emphasis on the study and impact of control system on the PACK performance.

6.1.2 Contribution 2

A novel 737 GTF on a B737-400 aircraft was developed targeting the left-hand side ECS PACK and is discussed in Chapter 4. This chapter is submitted to the Journal of Applied Thermal Engineering and is currently under review process.

The sensors to be installed were selected based on the operating temperature and pressure range of the PACK. The sensor lists included thermocouple, pressure transducer, humidity, and rotary sensor. The mass flow at selected locations has been measured using total-pressure head manufactured by the Cranfield Gas Turbine Laboratory and the static pressure and temperature readings measured at respective locations. Thorough laboratory tests have been conducted on the pressure transducer and thermocouple to understand the level of uncertainty in their measurements. Subsequently, the sensors were installed and the PACK was assembled back in-situ with the data-acquisition unit sitting inside the ECS bay. This setup allows a permanent base for experimental research on the 737 ECS PACK as the bay door can be closed off with a power supply and ethernet cable running out from the bay. Following that, a few tests were conducted to verify the usability of the GTF.

- i. *Functionality test*: The ECS was powered on with APU bleed and all the seals were manually tested for any leakages.
- ii. *Sensor continuity test*: The sensors installed were all checked for data collection. The locations from which data collection failed were highlighted and alternate routes were identified and discussed within Chapter 4.

- iii. *Temperature, pressure, and mass flow measurements*: Three sets of data under different ambient temperature with same target condition were collected and discussed. The data was found to capture the first principles physics of PACK at a component and system level.
- iv. *Consistency test*: Aircraft data was collected under different operating conditions, i.e. hot-cold demand with trim on-off. As theorized, data showed that for colder demand the mass flow through the core of the PACK increases to maximise cooling. It was also noted that for cold demand, regardless of the trim being on or off, the mass flow through the core of the ECS PACK increases to maximise cooling. Overall, the GTF captures well the first principles physics of the PACK performance under different operating conditions.

6.1.3 Contribution 3

In Chapter 4, the comparison study between aircraft data and simulation was presented and discussed. The PACK simulation model developed using SESAC for Boeing 737-800 model presented by Jennions et al [8], has been modified to replicate the Boeing 737-400 variant. As the turbomachinery and heat exchanger maps are unavailable for the -400, the existing maps incorporated within the -800 model was used for running simulation. It was identified that the simulation broadly captures the PACK performance except at the Merge_o, and PCK_o in terms of the temperature and at the ACM in terms of pressure. The maximum average relative difference between the data and simulation in terms of Temperature, Pressure and Mass flow was found to be 2%, 8% and 6%, respectively. These discrepancies were found to be consistent across all reference cases (hot-cold demand and trim on-off). The pressure difference at the ACM was suspected to be due to the mismatch in performance characteristics maps incorporated for the turbomachinery. Additionally, the mass flow variation between the data and simulation across the bypass valves (TCV) and the core was also considered to be another reason behind the higher discrepancies in terms of pressure and mass flow at the ACM. The difference in mass flow at the merge consequently impacts the energy balance where the hot and cold air is mixed, resulting in a difference

in temperature between data and simulation at the $Merge_o$, and PCK_o . Following are a list of learnings attained from this study:

- i. A perfect agreement for temperature throughout the core components of the PACK, as well as a reasonably acceptable match for the pressure considering the limitations associated with the resolution of the incorporated turbomachinery maps.
- ii. The control system greatly impacts the overall PACK performance as it directly impacts the mass flow split across the system.
- iii. Having the trim system on from the P5 overhead panel in the cockpit can substantially impact the overall energy balance across the PACK. It directly impacts the compression and expansion at the ACM affecting the amount of cooling attained by the PACK.
- iv. The data collected at ground operation with single PACK running suggested that under colder demand, the trim system had no practical implication on the PACK performance and therefore can be maintained off.

6.1.4 Contribution 4

A comprehensive study on the control system (valves and PACK protection system) and verification of their operation based on aircraft data from 737 GTF was provided in Chapter 5. Aircraft data was also used to detect ram door fault occurrence. This chapter was published in the Journal of Thermal Science and Engineering Applications [9]. The list below gives a summary of different aspects of learning associated to the control system:

- i. The PACK is found to be governed by a control system which has three different elements, mass flow control through PACK valve (PV), temperature control through Temperature Control Valve (TCV) and ram air modulating door, and PACK protection system.
- ii. The PV is pneumatically driven and pneumatically actuated, therefore it does not have any dedicated electronic sensors. On the contrary the TCV is electrically driven based on the thermal sensor and reading, and it is pneumatically actuated. In Chapter 5 details on the working principle of both the valves were discussed in detail.

- iii. The PACK protection system prevents the system from overheating by utilising three temperature switches as discussed in Chapter 5. Aircraft data collected from the 737 GTF is used to demonstrate normal operating condition across each thermal switches and the temperature control at the WS_o and PCK_o .
- iv. The fault detection capability of the 737 GTF was demonstrated using data collected for an abrupt PACK trip occurrence. The data suggested CMP_o temperature to reach threshold limit which caused the activation of the PACK protection system. Based on CMP_o and PHX_o temperature readings, the root cause of the PACK trip was discovered to be due to closing of the ram door. The ram door closure resulted in less cold mass flow through the PHX cold side, consequently making the heat exchanger ineffective.
- v. The integral controller embedded within SESAC was fine-tuned to achieve temperature, pressure, and mass flow simulation data under healthy and multiple level of component degradation. The PHX degradation simulation results were presented and discussed in Chapter 5 to demonstrate that the controller system can capture the engineering and physics of the PACK under both health and degraded functional scenarios.
- vi. Finally, the PV and TCV malfunction simulation study in terms of temperature, pressure and mass flow was presented and discussed in Chapter 5.

6.2 Future Work

The experimental work with the ECS does not end with the work conducted in this PhD, rather, the GTF developed opens doors to numerous future research activities. For which it is first necessary to address to the lessons learned and assumptions taken during this research work and extend the sensor installation to bleed air system, mixing manifold and cabin to complete the instrumentation of the entire ECS. Following that the GTF can be used for humidity analysis and fault mode studies.

6.2.1 Improvement of existing Ground Test Facility

From the experimental data analysis demonstrated in chapter 4 it is evident that the mass flow measurements are greatly influenced by the presence of uncertainty. It also has been showed that the mass flow distribution across the hot and cold side of the PACK impacts the overall PACK performance. Even though the mass flows obtained for this research falls within the calculated uncertainty limit based on the maximum error associated to the sensors used, the results can be further improved by incorporating differential pressure transducers for the mass flow measurements. Furthermore, the bleed mass flow at the inlet of the PACK was estimated based on mass flow continuity theory using the measured mass flow at the core and the pTCV location. The broken pitot-static tube installed at the inlet of the PACK can be fixed to measure the actual bleed mass flow.

Considering the lessons learned based on the experimental work and the evaluation of test data carried out in this PhD, the following list of improvements to the existing setup are recommended:

- i. The pressure sensors used for the mass flow measurement can be replaced with the pressure differential sensors. This will improve the measurement uncertainty for mass flow as suggested by a sister project in [10].
- ii. The PV inlet mass flow sensor in the current set-up is damaged, this can be corrected with some efforts to dismantle the required section(s) of the PACK, and its reinstallation post correction.
- iii. The ram mass flow has been assumed based on data provided by Boeing, therefore, pitot static probe can be installed at the ram inlet, attached to a pressure differential sensor for measurement of the ram mass flow.
- iv. A non-intrusive sensor can be installed on the turbine outlet duct to measure the turbine outlet temperature.

The existing set-up provides performance data of the PACK only. One of the key learnings from this PhD is the realisation of the PACK performance interdependencies with the upstream (bleed air system) and the downstream

systems (i.e. mixing manifold, air distribution and trim). The installation of non-intrusive temperature sensors on these systems will allow insights on how the PACK-zone controller is regulating the temperature throughout the PACK under imposed cabin demand. The acquisition of temperature data from the PACK through to the cabin can allow insights on how the characteristics of the PACK upstream and downstream systems influence the control of the TCV and trim valves. This information can then allow systematic testing of the PACK with traceable control system decision, allowing acquisition of robust PACK performance data that obeys both the physics and engineering of the overall system.

6.2.2 Humidity Data Analysis

One of the key aspects of the ECS is to regulate humidity, for which it uses a set of heat exchangers (RHX and CHX) and a WS. To study the HPWS relative humidity was measured across each component for all the reference cases. However, due to time restriction it was not possible to analyse the humidity variation across the HPWS. Based on the temperature, pressure and relative humidity measurements, the thermodynamic properties of the gas-vapour mixture can be evaluated. Assessment of air properties within the HPWS will help understand fault occurrences and its implication on HPWS performance characteristics. Furthermore, the specific humidity of the air within HPWS for the reference cases can be obtained by using a psychrometric chart and the measured temperature, pressure, and relative humidity. It is also necessary to perform tests on the humidity sensors installed on the GTF to estimate the level of uncertainty associated with the measurements. This can support verification of the humidity modelling within SESAC. Subsequently, the degradation simulation study can be performed using SESAC on the HPWS components.

6.2.3 Experimental Degradation Simulation

The 737 GTF is heavily instrumented with temperature and pressure sensors at the inlet-outlet of each component within the PACK. In this research the fault capturing capability of the GTF was demonstrated using data from the aircraft in Chapter 5 through identifying ram door malfunction. This GTF can also be used

to perform other component degradation experimental investigation, tabulated in **Error! Reference source not found..**

Table 6-1 Preliminary list of faults that will be experimentally tested

Fault modes	Conditions
Heat exchanger fouling (PHX and SHX)	Between 0% open - 90% open in intervals of 10%
Valves malfunctioning (PV and TCV)	Between -30° to +30° at an increment of 10°
Ram air door sticking	Between 0% open - 90% open in intervals of 10%

With regards to the PHX and SHX degradation, the effectiveness (ϵ) of the heat exchanger depends on the mass flow and inlet temperature at the hot and cold side as shown in Eq. 6-1. In SESAC, the ϵ_{maps} is estimated from a performance map based on hot and cold mass flow across the heat exchanger [11]. Based on this, the PHX and SHX cold (ram) side can be covered to simulate blockage. The drop in cold mass flow due to blockage reduces the HX effectiveness and hence increases the $\text{PHX}_{\text{h,o}}$ temperature. The data collected can then be used to verify the heat exchanger degradation analysis using SESAC presented by Jennions and Ali in [11].

$$T_{\text{PHX,ho}} = T_{\text{PHX,hi}} - \epsilon_{\text{maps}}(T_{\text{PHX,hi}} - T_{\text{ram,i}}) \quad (6-1)$$

The Ram air door sticking has similar impact as the PHX and SHX degradation, as for this failure mode the mass flow in the cold side also decreases, hence, impacting the HX effectiveness. The ram door malfunction demonstrated in Chapter 5 demonstrates 100% blockage. For future work the ram air inlet area can be covered at a percentage of the area to gradually decrease the ram mass flow and collect data for ram air door sticking failure mode.

The mass flow across the core is regulated by the PV and TCV. The functionalities of the valves are explained in Chapter 4. It is understood that the opening of the primary TCV is regulated by an electric motor based on the temperature readings. A potentiometer can be used to rotate the motor to obtain desired opening of the valve. This will allow to manually regulate the valve opening to simulate fault occurrence. In case of the stand-by TCV there is a built-in manual override knob that can be used for adjusting the opening of the valve. The data collected for TCV malfunction at different angle can help in understanding the impact of the fault occurrence on the PACK performance and can also be used for the verification of the fault simulation analysis presented in Chapter 4. Finally, the findings from both the healthy and fault injection experimental investigation using the 737 GTF will support development of the ECS diagnostic solutions and identification of optimised sensor locations to detect maximum fault occurrences.

References

1. Zhang G., Wang J., Lv Z., Yang Y., Su H., Yao Q., et al. A integrated vehicle health management framework for aircraft. 2015 IEEE Conference on Prognostics and Health Management (PHM). 2015; : 1–8. Available at: DOI:10.1109/ICPHM.2015.7245034
2. Figuero DV. Diagnostic Capability for Environmental Control Systems. Universidad Politécnica de Madrid, Cranfield Univeristy; 2017.
3. Skybrary. B738, Glasgow UK, 2012. 2012. Available at: https://www.skybrary.aero/index.php/B738,_Glasgow_UK,_2012 (Accessed: 26 June 2019)
4. AeroInside. Yan Boeing 737-400 near Kiev on Jun 23rd 2018, loss of cabin pressure. 2018. Available at: <https://www.aeroinside.com/item/11657/yan-b734-near-kiev-on-jun-23rd-2018-loss-of-cabin-pressure> (Accessed: 1 March 2020)
5. Skybrary. B735, en-route, SE of Kushimoto Wakayama Japan, 2006. 2006. Available at: https://www.skybrary.aero/index.php/B735,_en-

- route,_SE_of_Kushimoto_Wakayama_Japan,_2006 (Accessed: 26 June 2019)
6. Skybrary. B737 en-route, Glen Innes NSW Australia, 2007. 2017. Available at: https://www.skybrary.aero/index.php/B737_en-route,_Glen_Innes_NSW_Australia,_2007 (Accessed: 26 June 2019)
 7. Chowdhury S., Ali F., Jennions I. A Methodology for the Experimental Validation of an Aircraft ECS Digital Twin Targeting System Level Diagnostics. Proceedings of the Annual Conference of the PHM Society 2019. 2019. pp. 1–11. Available at: DOI:<https://doi.org/10.36001/phmconf.2019.v11i1.888>
 8. Jennions I., Ali F., Miguez ME., Escobar IC. Simulation of an aircraft environmental control system. Applied Thermal Engineering. May 2020; 172: 114925. Available at: DOI:[10.1016/j.applthermaleng.2020.114925](https://doi.org/10.1016/j.applthermaleng.2020.114925)
 9. Chowdhury S., Fakhre A., Jennions IK. Boeing 737-400 Passenger Air Conditioner Control System Model for Accurate Fault Simulation. Journal of Thermal Science and Engineering Applications. 2 February 2022; : 1–18. Available at: DOI:[10.1115/1.4053740](https://doi.org/10.1115/1.4053740)
 10. Skliros C., Ali F., Jennions I. Experimental investigation and simulation of a boeing 747 auxiliary power unit. Journal of Engineering for Gas Turbines and Power. 2020; 142(8). Available at: DOI:[10.1115/1.4047771](https://doi.org/10.1115/1.4047771)
 11. Jennions I., Ali F. Assessment of Heat Exchanger Degradation in a Boeing 737-800 Environmental Control System. Journal of Thermal Science and Engineering Applications. 1 December 2021; 13(6). Available at: DOI:[10.1115/1.4050324](https://doi.org/10.1115/1.4050324)