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Assessment of Heat Exchanger Degradation in a Boeing 737-800 Environmental Control System

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Abstract

There are a number of systems on an aircraft working together, in harmony, to produce safe and trouble free flight. The Environmental Control System (ECS) is one of these systems, and its failure is a major contributor to unscheduled maintenance, particularly in older aircraft. The ECS is composed of several complex sub-systems and components, but at its heart is the passenger air conditioner (PACK). The PACK is prone to degradation, which can lead to the functional failure of the ECS. Often its degradation is masked by the overall ECS control system and this can, ultimately, result in the ECS shutting down and extensive maintenance being required. There are a number of critical fault modes associated with the PACK, and in this paper those modes associated with the primary and secondary heat exchangers are explored.

A robust ECS simulation framework called SESAC (Simscape ECS Simulation under All Conditions) has previously been implemented, calibrated, and tested, against data from healthy systems. Here the simulations are extended to cover degraded components in a representative Boeing 737-800 aircraft PACK model. Fault modes such as blockage and fouling are assessed for the primary and secondary heat exchangers of the PACK. Simulation results, in terms of temperature, pressure and mass flow at various degradation severities, are presented and discussed. The results highlight the interdependency between the PACK components, and the strong association between the primary and secondary heat exchanger performance. The reported simulation methodology and findings serve as a further step towards the goal of formulating a cost-effective ECS fault isolation and diagnostic solution.

Nomenclature

Acronyms

Alt	Altitude (m)
ACM	Air Cycle Machine
CHX	Condenser
CPCS	Cabin Pressure Control System
DS	Degradation Severity
ECS	Environmental Control System
HPWS	High Pressure Water Separator
PACK	Passenger Air Conditioner
PO	PACK Outlet
PV	PACK Valve
PHX	Primary Heat Exchanger
RAI	Ram Air Inlet
RC	Reference Case
RH	Relative Humidity (%)
RHX	Reheater
SESAC	Simscape ECS Simulation under All Conditions
SHX	Secondary Heat Exchanger
TCV	Temperature Control Valve
V&V	Validation & Verification
WS	Water Separator

Subscript

C_{PR}	Compressor pressure ratio
CMP_i	Compressor inlet
CMP_o	Compressor outlet
$CHX_{h,i}$	Condenser hot inlet
$CHX_{h,o}$	Condenser hot outlet
$CHX_{c,i}$	Condenser cold inlet
$CHX_{c,o}$	Condenser cold outlet
N_c	Compressor rpm
N_t	Turbine rpm
N	ACM rpm
P	Pressure (kPa)
P_{BAS}	Bleed air pressure (kPa)
P_{Cab}	Cabin Pressure (kPa)
P_{vi}	PACK valve inlet
P_{vo}	PACK valve outlet
$PHX_{h,i}$	Primary heat exchanger hot inlet
$PHX_{h,o}$	Primary heat exchanger hot outlet
P_{amb}	Ambient Pressure (kPa)
PCK_o	PACK outlet
$RHX_{h,i}$	Reheater hot inlet
$RHX_{h,o}$	Reheater hot outlet
$RHX_{c,i}$	Reheater cold inlet

$RHX_{c,o}$	Reheater cold outlet
$SHX_{h,i}$	Secondary heat exchanger hot inlet
$SHX_{h,o}$	Secondary heat exchanger hot outlet
T_{amb}	Ambient Temperature (K)
T_{ci}	Cold side inlet temperature (K)
TRB_i	Turbine inlet
TRB_o	Turbine inlet
T_{co}	Cold side outlet temperature (K)
T_{PR}	Turbine pressure ratio
T_{BAS}	Bleed air temperature (K)
T_{cab}	Cabin temperature (K)

Greek Symbols

$\dot{m}$	Mass flow (kg/s)
$\dot{m}_c$	Cold mass flow (kg/s)
$\dot{m}_{cab}$	Cabin mass flow (kg/s)
$\dot{m}_h$	Hot mass flow (kg/s)
$\dot{m}_{ci}$	Cold side inlet mass flow (kg/s)
$\dot{m}_{co}$	Cold side outlet mass flow (kg/s)
ϵ	Effectiveness (%)
ϵ_{maps}	Effectiveness from the maps (%)
ρ_h	Density hot side (kg/m ³)
γ	Ratio of specific heats = C_p/C_v

1. Introduction

1.1 Background

The aerospace industry spends billions of dollars every year on maintenance, repair and overhaul (MRO) of commercial aircraft. In 2017 a study conducted by the International Air Transport Association reported a figure of \$76 billion [1]. Unscheduled maintenance activities have a significant impact on these costs. Consequently, the aviation industry is currently exploring innovative health management solutions that aid maintenance of aircraft key systems, sub-systems and components, based on prediction based maintenance approaches using real-time condition monitoring techniques [2-5]. Legacy aircraft such as the Boeing 737 are particularly vulnerable, as they lack appropriate sensors in order to support the implementation of a cost-effective and lean health management strategy.

Amongst others, the aircraft environmental control system (ECS) has been reported as a major driver of unscheduled maintenance in older aircraft [7]. The primary purpose of the ECS is to maintain a safe and comfortable environment for passengers throughout the aircraft cabin. The ECS is one of the major systems of the aircraft and is composed of several complex sub-systems and components, shown in Figure 1 for a typical legacy aircraft. The ECS receives bleed air from either the main engines or the auxiliary power unit (APU). The bleed air is conditioned for temperature, pressure and humidity, and is supplied to the cabin using a sophisticated air distribution system. The heart of the ECS system, that enables the conditioning of the bleed air, is called the passenger air conditioner (PACK). The PACK is prone to degradation, which can lead to the functional failure of the ECS system. Often these degradation modes are masked by the overall ECS control system and can result in unscheduled maintenance [8].

In order to propose innovative, safe and efficient health management solutions for the ECS, the authors in reference [8] set three goals:

- i. Advance the level of scientific understanding towards how the PACK and its components' useful life degrade under a wide-range of operating scenarios.
- ii. The quantification of the level of impact the sub-system and component level performance interdependencies have towards determining the optimum functionality of the PACK.
- iii. Identification and quantification of the sub-system and component health state indicators needed in order to conceive new diagnostic and prognostic solutions.

A first step towards the realisation of these goals is the development of an ECS simulation framework: a cost effective and efficient approach for providing performance simulation of the ECS under a wide range of operational and functional scenarios. The IVHM Centre, Cranfield University, in collaboration with The Boeing Company, have developed an ECS simulation capability called SESAC (Simscape ECS Simulation under All Conditions). The theoretical and computational development of SESAC, as well as its successful implementation for the modelling, simulation, and verification and validation (V&V) of a Boeing 737-800 PACK model against actual data has been previously reported [8]. In the current paper the authors have further extended the research to simulate critical fault modes of the PACK in order to assess its performance characteristics under various fault scenarios. The fault modes of interest are those highlighted by the operators and correspond to the PACK primary and secondary heat exchanger degradation, the failure in these components often being compensated for by the way the PACK operates. This is doubly inconvenient as it means that when maintenance is indicated, several components probably need attention, resulting in major maintenance and delay in return to service.

The overall aim of the work is to understand the physics and engineering of the PACK at system and component level, for various heat exchanger degradation scenarios, in order to facilitate the formulation of an effective diagnostic and condition monitoring solution.

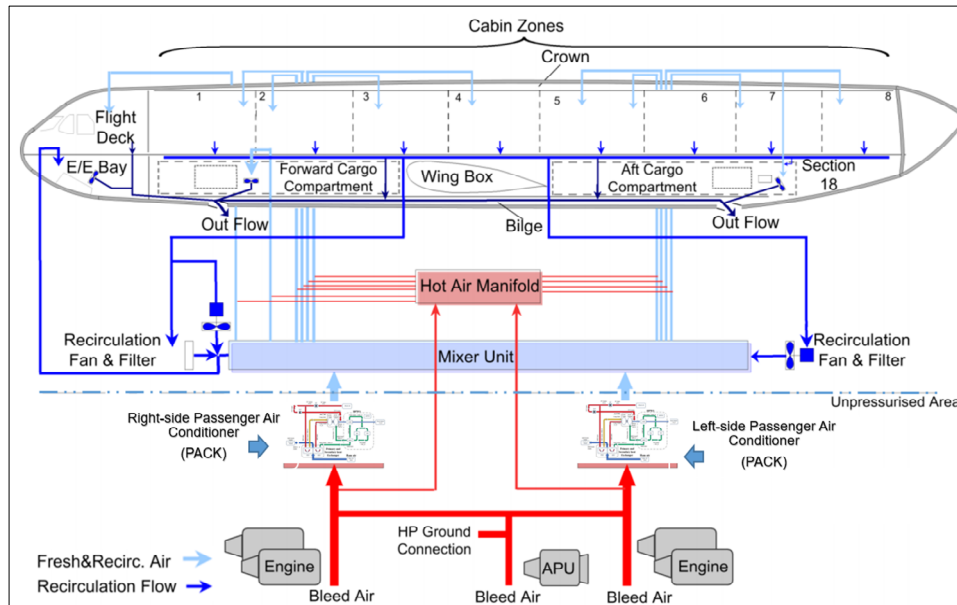


Figure 1. Layout of a commercial aircraft ECS.

1.2 Description of aircraft PACK

The primary function of the PACK is to condition the bleed air to meet the temperature and pressure demanded by the flight crew, to maintain a comfortable environment for the passengers and the crew. The conditioned air from the PACK is also used as the cooling air to cool the aircraft avionics, shown as the E/E (Electronic / Electrical equipment) Bay in Figure 1. There are normally two PACKs in most narrow and wide-body civil aircraft, and they are generally installed in parallel on either side (left-hand and right-hand side) of the aircraft centreline, on the underside of the fuselage.

A schematic of the B737-800 PACK is illustrated in Figure 2. The bleed air is supplied to the PACK at high temperature and pressure from the engines or the Auxiliary Power Unit (APU). Using the ram air (cold air that is ducted from outside the aircraft) as a heat sink, the PACK removes heat from the bleed air in the primary heat exchanger (PHX) and the secondary heat exchanger (SHX). The PACK also reduces the bleed air pressure and further decreases its temperature through the turbine incorporated in the Air Cycle Machine (ACM), and extracts water content using a High Pressure Water Separator (HPWS) in order to comply with the cabin environment requirements. The overall flow through the system is governed by the PACK Valve (PV), while that bypassing the cooling loop is controlled by the Temperature Control Valve (TCV).

The PHX and SHX play a pivotal role in enabling the PACK to work efficiently, and their functionality is highly dependent on the optimal utilisation of the ram air. The intake section of the PHX on a B737-800 is shown in Figure 3(a), and an illustration of its cross-section and airflow passages shown in Figure 3(b). The SHX has the same geometry and size as the PHX, and they are mounted side-by-side, as illustrated in Figure 3(c). The ram air intake (RAI) is designed as a common intake, supplying both the PHX and SHX with equal amounts of cold air flow. This cold air is captured from outside the plane via an intake, shown in Figure 3(d).

RAI, PHX, and SHX are critical components of the PACK. They are subjected to degradation that can potentially have a significant detrimental impact on the PACK's safe and efficient operation.

Furthermore, the failure in these components is often masked by the PACK's control system and so can be difficult to troubleshoot.

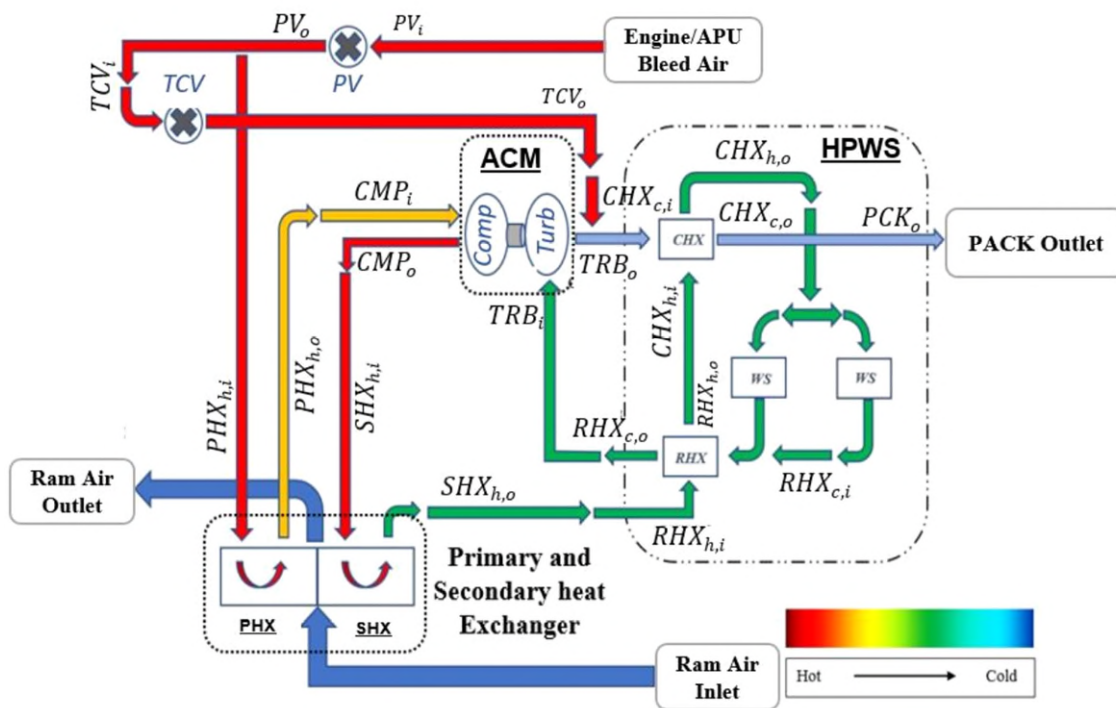


Figure 2. Component level schematic of the B737-800 PACK.

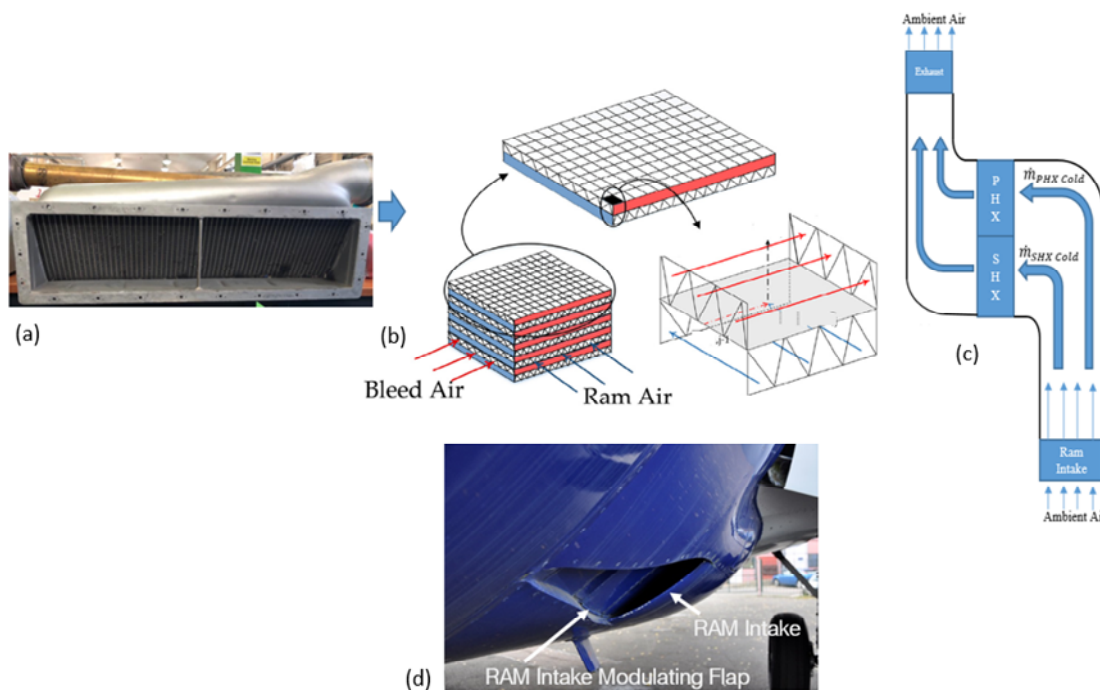


Figure 3. (a) Left-hand side PACK PHX, (b) HX cross-section with airflow passages, (c) and (d) ram intake duct supplying cold airflow to the PHX and SHX

1.3 PACK heat exchanger degradation

In the last decade, PACK heat exchangers have been extensively investigated. These heat exchangers are made of fin and plate assemblies, allowing a cross-flow of cold ram air over the hot bleed airflow as shown diagrammatically in Figure 3(b). A simple fault occurrence can escalate and lead to functional failure of the ECS. For instance, a Boeing 737-700 flight to Melbourne in 2007 [9] experienced a failure of the right hand engine bleed during take-off. The flight was continued but subsequently, during the climb to Flight level 350 (35000ft), the left air conditioning PACK valve failed, this resulted in the PACK shutting down, and an emergency descent followed with passenger oxygen masks deploying as the cabin altitude exceeded 14000 feet. The failure of the PACK valve can also be caused by a malfunction of the ram air intake modulator, limiting the amount of cold mass flow over the heat exchangers, resulting in PACK overheating. In such a scenario the control system shuts the PACK valve.

Blockage and fouling of heat exchangers are two main types of degradation modes reported in the existing literature associated with the aircraft PACK [10]; both affect the heat exchanger ram side air inlet [11, 12]. Blockage refers to the sticking of relatively large foreign objects in the ram air inlet, leading to a reduction in the cold side inlet mass flow to the primary and secondary heat exchangers. It can also be due to an accumulation of small size foreign objects that can travel through the ram intake and stick to the ram side inlet of the PHX or SHX, causing a reduction in inlet area and therefore reduced mass flow.

Fouling is somewhat more complicated. The ambient ram cooling air, acting as the cold streams for the PHX and SHX, contains contaminants and debris that are deposited on the PHX and SHX surfaces. Particulate accumulation is a function of flowrate, concentration of contaminants, and system temperatures and pressures. The accumulation of such contaminants on the heat exchanger surface significantly reduces its heat transfer efficiency and performance over time, leading to significant costs from maintenance and component failures [14]. Therefore, the prediction, identification and isolation of heat exchanger fouling have been the subject of several studies. The physical phenomenon of particulate fouling is currently not well understood, making fouling behaviour challenging to predict.

A recent review paper [12] on aircraft heat exchangers highlights PACK heat exchanger fouling as one of the main causes of overheating. When excessive levels of particulates are deposited in the matrix, the thermal performance of the heat exchanger decreases, the PACK reaches higher than acceptable operational temperatures, and must be isolated. This results in the control system shutting down the overheating PACK to prevent further damage and the possibility of a fire. Rectification can only be achieved by removing the PACK from the aircraft, and returning the unit back to the Original Equipment Manufacturer for deep cleaning to remove the contaminants. This can have a significant impact on the operational availability of the aircraft.

An experimental study on cold air side heat exchanger fouling was conducted by Purdue University [15]. Their findings suggest that a significant reduction in heat transfer effectiveness occurs due to particulate fouling in plate-fin type heat exchanger. Figure 4 shows dust and debris particles that have coated the surface area of the cold side of the heat exchanger, forming a solid layer on the walls. This results in an increase in thermal resistance and a reduction in the thermal effectiveness of the heat exchanger. In a similar manner, debris in the air is accumulated on the forward face of the PACK heat exchangers as the ram air comes directly from outside without any filtration. This reduces the effectiveness of the heat exchangers. To resolve this issue, from the design perspective, Wright et al. [12] proposed a method of using electrostatic filtering to remove these debris particles.

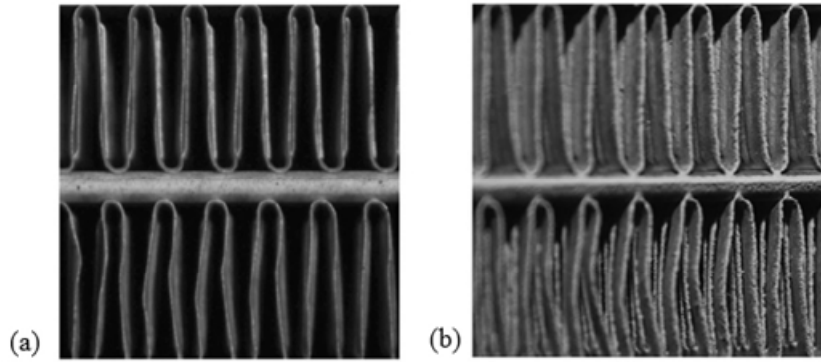


Figure 4. Air to air, plate-fin type heat exchangers, adopted from [19], (a) Clean, (b) Particulate fouled

1.4 Scope of present work

This paper is dedicated towards understanding the physics and engineering of the PACK, at system and component level, under various faulty scenarios in order to facilitate the formulation of an effective diagnostic and condition monitoring solution. The SESAC simulation framework is used to assess the health state parameters in terms of the temperature, pressure and mass flow (T , P , $\dot{m}$), for the critical degradation modes (i.e. fouling and blockage) associated with the PHX and SHX as well as the RAI. The discussion of the results focuses on the quantification of the PACK performance characteristics, with specific emphasis on highlighting the interdependencies between the various components when exposed to degradation.

2. Simulation methodology

2.1 ECS simulation framework

An ECS simulation framework (SESAC) is used to simulate the PACK degraded performance at sub-system and component level. SESAC offers a library of modules that can be assembled to model any PACK configuration. It is capable of simulating the health state indicating parameters – T , P , $\dot{m}$ - of the PACK throughout the aircraft operating envelope and under a wide range of functional scenarios. The overall theoretical and computational development of SESAC, as well as its verification and validation, has been thoroughly reported by the authors in reference [8].

2.2 Reference fault simulation model

Figure 5 presents the compiled PACK model based on the SESAC library. The model configuration in terms of the architecture and flow sequence mirrors the B737-800 schematic presented in Figure 2. The PACK receives input bleed air at high temperature and pressure from the engine, the quantity of which is controlled by the PACK valve (PV). The overall model is comprised of many different modules: heat exchangers, a pipe merge, the HPWS, the ACM, 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, and the rest is bypassed, making the hot stream. In the cold stream, the flow proceeds through the heat exchangers, which use the ram air as a heat sink to considerably drop the temperature. The compressor, positioned between the heat exchangers, increases the air pressure in order to maximise the refrigeration effect through the turbine. The HPWS is composed of reheater, condenser and water extractor, allowing the extraction of water content prior to the expansion of the air in the turbine.

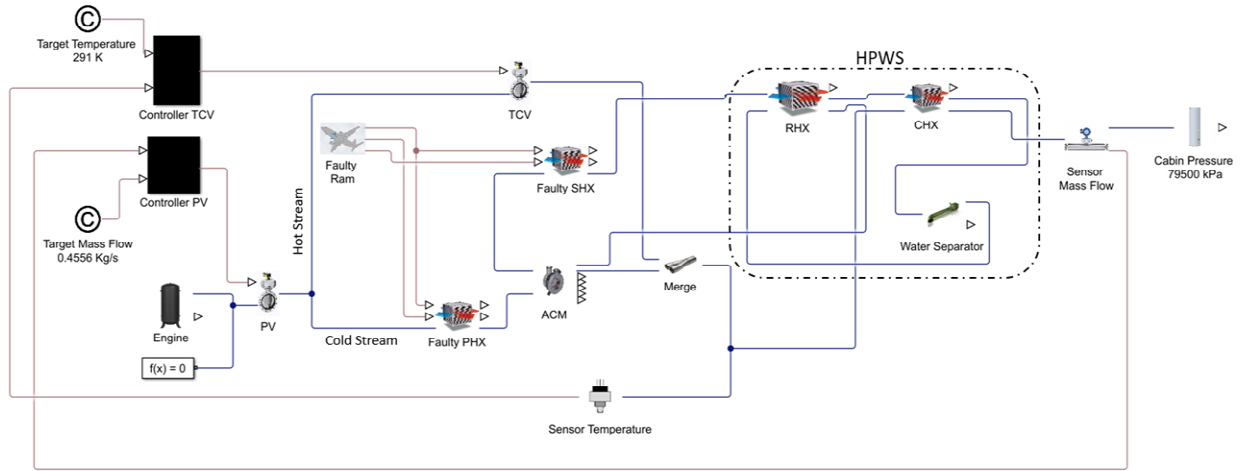


Figure 5. SESAC fault simulation model for the B737-800 PACK.

Once the air is expanded through the turbine, the cold air is mixed with the hot bypassed air, controlled by the TCV, in the merge module. The temperature at the outlet of the merge is monitored by a (virtual) sensor and feedback given, through a controller, to adjust the TCV valve setting until the imposed target temperature is achieved. This process ensures that for any given operating condition the PACK delivers the demanded target temperature to the mixing manifold system. The TCV also enables prevention of ice formation in cases where the turbine outlet temperature drops below freezing.

In reference [8] the authors report the overall development and simulation of the B737-800 model for two Reference Cases (RCs), representing PACK cruise operation at two different altitudes (RC1 - 28000ft and RC2 - 41000ft). The acquired results are corroborated against actual aircraft data at healthy conditions. In this paper the RC1 case, shown in Table 1, is adopted as a healthy baseline to assess PACK operation under degraded heat exchanger scenarios. The degradation modes of the PACK heat exchangers are simulated by injecting faults in the PHX, SHX and RAI. As shown in Figure 5 the respective components are replaced with their faulty PHX, SHX and ram equivalents. Discussion of the fault simulation of these components is presented in section 2.3 below.

Table 1. Reference Case 1 (RC1) aircraft operating condition

	Alt [ft]	Mach	Tamb [K]	Tamb [C]	Pamb [kPa]
RC 1	28000	0.761	232	-41	33

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 2: (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 P, T, specific humidity, and water content are required. (iii) Target output conditions, i.e. T, P and $\dot{m}$. (iv) Component health state, represented by the degradation severity (DS) which varies from 0 (healthy) to 1 (fully degraded).

Table 2. RC1 input boundary conditions to simulate the PACK performance in SESAC.

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]
	Alt	Aircraft Altitude	[m]
Ram (1: In flight)	M	Aircraft Mach number	[-]
	Area	Ram door total area	[m ²]
	%Open	Ram door opening in %	[%]
Bleed Air properties	T_{BAS}	Inlet temperature to PV	[K]
	P_{BAS}	Inlet pressure to PV	[Pa]
	SH_{BAS}	Inlet specific humidity at PV	[kg/k]
	CO_{BAS}	Inlet liquid water content at PV	[kg/k]
Target Conditions	P_{cab}	Cabin pressure	[Pa]
	T_{cab}	Cabin temperature	[K]
	$\dot{m}_{cab}$	Cabin mass flow	[kg/s]
Component health state	DS	Degradation severity	
	$DS_{PHX,f}$	PHX fouling	
	$DS_{PHX,b}$	PHX blockage	
	$DS_{SHX,f}$	SHX fouling	
	$DS_{SHX,b}$	SHX blockage	
	$DS_{ram,b}$	SHX blockage	

2.3 Modelling of the degradation modes

2.3.1 Fouling of PHX and SHX

In heat exchanger fouling, due to the ingestion of particles through the ram air intake, the thermal properties of the heat exchanger change. This is due to the deposition of particles on the heat exchanger, adding a thermally insulating material. This solid layer acts to increase the thickness of the wall, which adds additional thermal resistance to heat flow, augmented because the thermal conductivity of the fouling deposits is usually lower than that for the metals used for heat transfer surfaces. Furthermore, depending on the working fluid and flow operating conditions, the formed solid layer can also increase the hydraulic resistance of the fluid flow [7, 8].

Heat exchangers come in many forms, characterised by the circulation pattern of the hot and cold air streams. In civil aircraft, cross-flow heat exchangers, where hot and cold flows are directed through channels orthogonal to each other, are commonly used, although the exact configuration is not important to the modelling performed here. The overall formulation of a heat exchanger included in SESAC is reported in [1], and a short recap is given below in equations 1 to 4. Equation 4 is used to calculate the outlet temperature of the heat exchanger as a function of its effectiveness and the hot and cold side temperatures for a healthy component. For the degraded case, the degradation severity is introduced, highlighting the thermal effect of the fouling by modifying the effectiveness. Heat

exchanger performance maps correlate hot and cold side mass flows with effectiveness. The actual maps incorporated in the B737-800 simulation model are proprietary, and therefore their inclusion here is omitted, but Figure 6 shows a notional heat exchanger performance map for reference.

The relevant equations for the PHX and SHX effectiveness can be defined as:

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{\dot{m}C_{p,h}(T_{h,i}-T_{h,o})}{\dot{m}C_{p,min}(T_{h,i}-T_{ram,i})} = \frac{\dot{m}C_{p,ram}(T_{ram,o}-T_{ram,i})}{\dot{m}C_{p,min}(T_{h,i}-T_{ram,i})} \quad (1)$$

where the product $\dot{m}C_p$ is referred to as the stream capacity, and is defined for both streams as $\dot{m}C_{p,h}$ and $\dot{m}C_{p,ram}$.

The maximum possible heat exchange between the two streams is given by:

$$Q_{max} = \dot{m}C_{p,min}(T_{h,i} - T_{ram,i}) \quad (2)$$

where, $\dot{m}C_{p,min}$ can be either $\dot{m}C_{p,h}$ or $\dot{m}C_{p,ram}$.

In the code these equations are simplified by using a performance map similar to that shown in Figure 6. With the mass flow through the ram and hot streams as input, the effectiveness (ε_{maps}) can be read from the map and the heat exchanger outlet temperature obtained from:

$$T_{h,o} = T_{h,i} - \varepsilon_{maps}(T_{h,i} - T_{ram,i}) \quad (3)$$

The degradation severity can then be introduced to allow control of the heat exchanger fouling, resulting in:

$$T_{h,o} = T_{h,i} - (1 - DS) * \varepsilon_{maps}(T_{h,i} - T_{ram,i}) \quad DS = [0: Healthy - 1: Faulty] \quad (4)$$

ε = Effectiveness of heat exchanger[%]

$T_{h,i}$ = Hot inlet temperature[K]

$T_{ram,i}$ = ram inlet temperature[K]

C_p = Heat capacity at constant pressure[J/Kg. K]

DS = degradation severity[%]

$T_{h,o}$ = Hot outlet temperature[K]

$T_{ram,o}$ = ram outlet temperature[K]

$\dot{m}C_{p,ram}$ = ram stream capacity [J/Kg. K]

Q = Heat transfer[W]

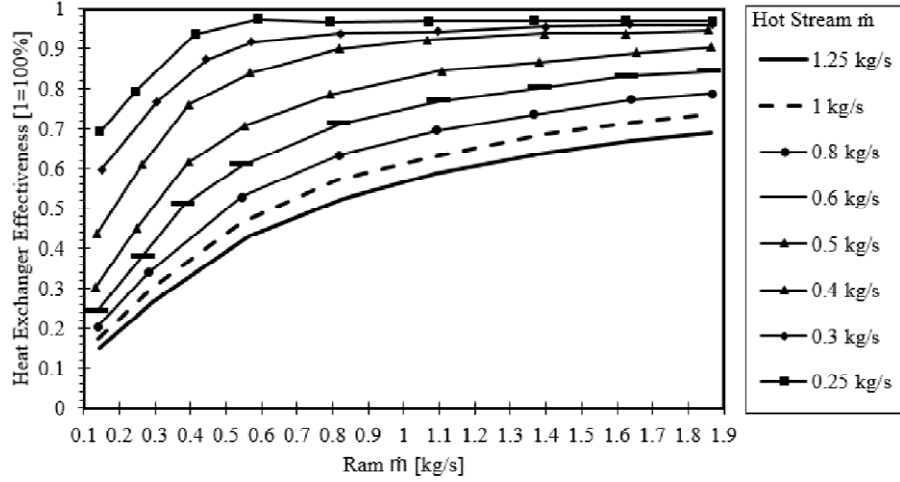


Figure 6. A notional effectiveness map for PHX and SHX.

2.3.2 Blockage of PHX and SHX

The sticking of relatively large dust particles, debris and/or random foreign objects (e.g. a bird), injected 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 SHX, and therefore there is a risk of large dust particles or foreign objects passing through the ram air intake.

The hot side intake, which receives hot bleed air from the main engine compressors when the aircraft is in flight, is filtered in the bleed air system. However, during ground operations, the bleed air is supplied by the APU without any filtration. Nevertheless, the likelihood of blockage on the hot side of the PHX and SHX is very low, as the bleed air has to pass through several components prior to reaching the PHX and SHX.

As illustrated in Figure 3(c), the ram intake is designed as a common intake for providing air flow to the PHX and SHX cold side inlets. On the actual aircraft, both heat exchangers are identical in terms of design, shape, weight, and size. The area of the ram air intake is the same for PHX and SHX, under healthy conditions, it is therefore assumed that the total amount of ram air flow for any given aircraft operating condition is equally divided between the PHX and the SHX. The equations used to calculate the total ram flow are given below, in section 2.3.3. For this fault mode, the simulation is modified to include a simple blockage in the PHX and/or SHX ram air inlets. This leads to a reduction in the mass flow through these pathways (illustrated in the PACK model shown in Fig. 5), which can subsequently reduce the effectiveness of the heat exchanger, as expressed in equation 1, by reducing the mass flow. Only the direct blockage effect is input. The incorporated faulty ram component in the PACK model shown in Fig. 5 includes the option to degrade the ram air flow supplied to the PHX and SHX independently under faulty conditions.

2.3.3 Blockage in ram air intake

The amount of ram air that can be achieved depends on the aircraft operating conditions: Mach number, ambient temperature and pressure (Table 2). The Mach number is a function of aircraft speed and the local speed of sound. The temperature and pressure at the ram inlet can be expressed using, [16]:

$$T_{ram} = T_{atm} \left\{ 1 + \left[\left(\frac{\gamma-1}{2} \right) * M^2 \right] \right\} \quad (5)$$

$$P_{ram} = P_{atm} + P_{atm} * FR * \left\{ \left[1 + \left(\frac{\gamma-1}{2} \right) * M^2 \right]^{\frac{\gamma}{\gamma-1}} - 1 \right\} \quad (6)$$

Based on the inlet area of the ram air conduit, the mass flow rate through it can be calculated using:

$$G_M = \frac{M}{\left[1 + \left(\frac{\gamma-1}{2} \right) * M^2 \right]^{\frac{\gamma+1}{2*(\gamma-1)}}} \quad (7)$$

$$\dot{m}_{ram} = \frac{G_M P_{ram} A_e}{\sqrt{\frac{T_{ram} R}{\gamma}}} \quad (8)$$

To account for the inlet modulating door the total area of the ram air conduit is corrected based on the position of the modulating flap. The corrected area is then treated as the effective area:

$$A_e = A_t * \text{Position of modulating flap} \quad \text{Position} = [0: \text{Closed} - 1: \text{Open}] \quad (9)$$

When the aircraft is stationary, the SESAC model requires the ram mass flow as an input boundary condition (Table 2).

Finally, the ram air component includes an option to degrade the ram air mass flow, due to blockage:

$$\dot{m}_{Ram} = \frac{G_M P_{ram} A_e}{\sqrt{\frac{T_{ram} R}{\gamma}}} * (1 - DS_{ram}) \quad (10)$$

$DS_{ram} = [0: \text{Healthy} - 1: \text{Fully Blocked}]$

T_{ram} = ram inlet temperature[K]

T_{atm} = Ambient temperature[K]

G_M = Mach function [-]

A_e = Effective area[m²]

P_{ram} = ram inlet pressure[kPa]

P_{atm} = Ambient inlet pressure[kPa]

M = Mach number[-]

A_t = Total area[m²]

FR = Recovery factor[-]

γ = Ratio of specific heats[-]

R = Gas constant[J/kg. K]

DS_ram = degradation severity [%]

2.3.4 Equivalency between Fouling and Blockage

Although stemming from two very different sources, as previously discussed, fouling and blockage have the same effect on the heat exchanger. This is obvious from Figure 6, where a reduction in $\dot{m}_{ram}$ (for a given $\dot{m}_{hot}$) can be seen to reduce the effectiveness. Thus, blockage (which directly results in $\dot{m}_{Ram}$ reducing) is equivalent to fouling (which directly reduces effectiveness). Both inputs are allowed in the code, but for the PHX and SHX results in this paper only fouling will be shown and discussed. For the RAI results, blockage will be used as it is the most appropriate mechanism.

3. Results and discussion

This section presents the B737-800 PACK fault simulation results, for the degradation modes described in section 2.3. The results acquired for the PHX and SHX fouling are elaborated in terms of T, P and $\dot{m}$

throughout the PACK at various severities. Subsequently, in a similar fashion, the RAI degradation results are also presented.

3.1 PHX fouling results

Simulation of the healthy baseline case was calibrated with available data, by tuning the ram air flow to match the PHX outlet temperature [8]. Both the temperature and mass flow controllers have the healthy baseline target temperature, and corresponding mass flow, set as targets during simulation of all degraded cases. From this baseline, fouling is simulated by increasing the degradation severity (equation 4). Figure 7 presents the acquired results in terms of temperature, pressure and mass flow; an interpretation of these simulation results is given below.

Heat exchangers are designed and built as mechanical devices to enable heat transfer between fluids. In the context of their operation in the PACK, the cold side mass flow is the ram sink air and the hot side is the PACK flow, as illustrated in Figure 3. Heat transfer will take place between the two streams, and the ram flow heats up while the bleed flow cools down. The degree of heat transfer is governed by the effectiveness, and a simple energy balance across the heat exchanger walls. The drop in effectiveness of the PHX due to fouling therefore results in a reduced temperature drop relative to baseline. This is shown in Figure 7(a), where the healthy PHX outlet temperature increases significantly between healthy and severely degraded. Figure 7(a) gives the numeric values of the temperature difference between healthy and severely degraded (DS=0.9) at the major stations (see Figure 2) of interest throughout the PACK.

The incorporation of the SHX in the PACK is to provide a supplementary heat exchanger in order to compensate for the unwanted temperature rise due to compression. Also to serve as a backup unit, compensating for any short falls occurring in the amount of heat transfer from the PHX under abnormal operating conditions. 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. The reason for this goes back to Figure 3(c). Effectively the PHX and SHX are acting together as one large heat exchanger, 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.

At the merge component (Figure 5), continuity and energy have to be satisfied. Referring to the flow through the TCV as ‘hot’ and that through the heat exchangers and ACM as ‘cold’, these equations are:

$$\dot{m}_{engine} = \dot{m}_{cold} + \dot{m}_{hot} \quad (11)$$

$$\dot{m}_{engine} C_p T_{target} = \dot{m}_{cold} C_p T_{cold} + \dot{m}_{hot} C_p T_{hot} \quad (12)$$

In addition, as there can be no pressure discontinuity at the merge, the pressure at the turbine outlet and the TCV outlet are the same.

There are two control loops in the system, one for temperature and one for flow (Figure 5). 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 (engine) mass flow.

Considering equation 12 and the temperatures from Figure 7(a), T_{target} and T_{hot} are known, T_{cold} has risen, due to PHX degradation, so only the mass flow can be redistributed to satisfy energy at the merge. To do this $\dot{m}_{cold}$ increases, to allow cooler flow through the system, while $\dot{m}_{engine}$ is kept constant. The TCV closes to drop $\dot{m}_{hot}$ and the PV opens to keep $\dot{m}_{engine}$ constant, hence $\dot{m}_{cold}$ increases, as shown in Figures 7(c) and 8(a). The extremely degraded cases, where $\dot{m}_{engine}$ falls, will be dealt with later.

This broadly accounts for the temperature and mass flow behaviour shown in Figures 7(a) and 7(c), but does not explain the build-up of pressure between the PV and compressor inlet (Figure 7(b)). This occurs because the turbine inlet temperature is relatively constant and so its expansion, to a temperature that can be mixed to accommodate T_{target} , is also relatively fixed. The turbine and compressor are on the same spool and hence the compressor receives the turbine work, with account for mechanical efficiencies, directly. As this work is nearly fixed, the compressor pressure ratio is close to that of the healthy case, in fact slightly less, due to increased inlet temperature, as shown in Figure 8(b). This results in the backpressure seen between the pack valve and compressor inlet. As the TCV has closed, the compressor cannot pump more to clear this pressure and drive more flow through the cold stream due to the limitations of the turbine.

As the degradation increases there comes a point where the PV is fully open and cannot deliver any more flow (Figure 8(a)). At this point $\dot{m}_{engine}$ decreases in order to satisfy the merge conditions, given the PV cannot open any more.

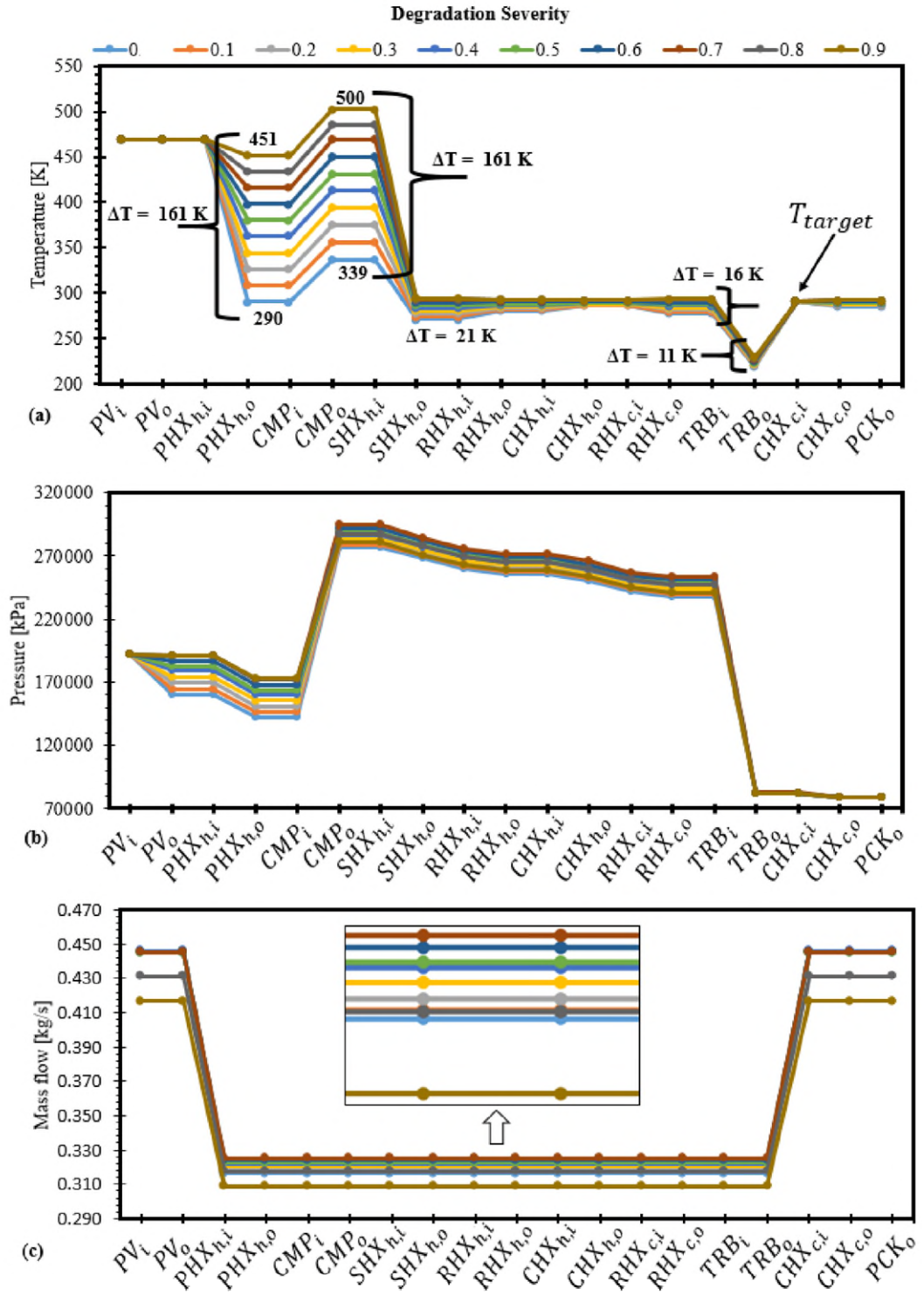


Figure 7. Simulation results for PHX fouling: (a) Temperature, (b) Pressure, (c) Mass Flow.

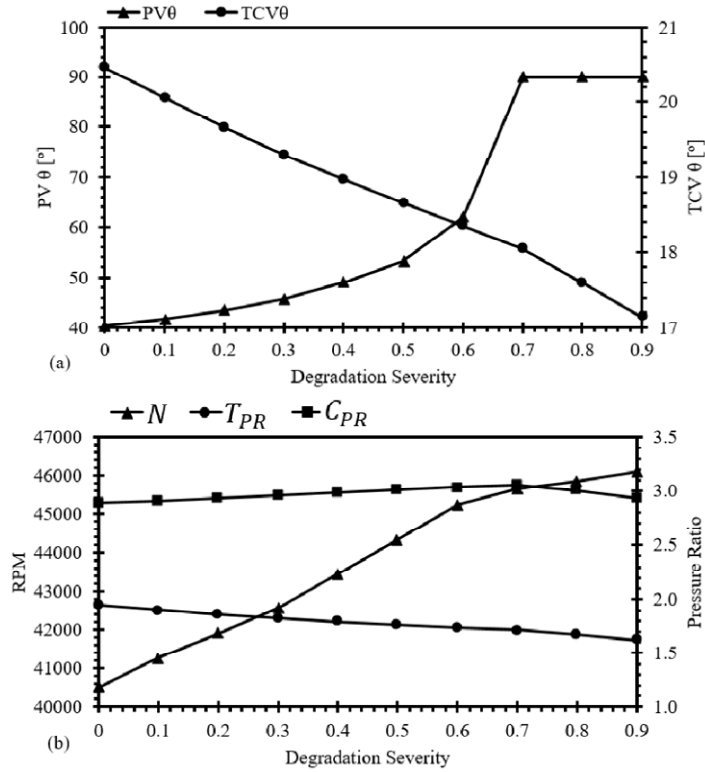


Figure 8. Simulation results for PHX fouling: (a) PV and TCV valve angles, (b) ACM characteristics.

3.2 SHX fouling results

When the SHX is fouled a different, simpler, picture than that just presented for the PHX emerges, due to its location in the overall PACK. Figure 9 presents the simulation results in terms of T , P and $\dot{m}$ for different levels of degradation. As the fouling increases, the SHX outlet temperature rises (Figure 9a), consistent with the SHX not being able to remove as much heat as its healthier counterpart.

The HPWS's heat exchangers take temperature out of the cold stream initially (RHX_h and CHX_h) but end up putting it back in (RHX_c and CHX_c), a consequence of the air passing through both sides of these heat exchangers at different points in the system. This results in the curious rise in temperature downstream of the fixed temperature merge point. Clearly, this is not as intended, but if the fixed temperature point is moved to PO the overall results remain the same. No benefit from water separation can be claimed, as this case is at 28000 ft. and hence the air is dry.

The SHX temperature rise is passed downstream, and the turbine inlet temperature rises significantly. The turbine is able to remove some of the excess heat, but its outlet temperature rises. In order for the desired temperature to be met at the merge (Figure 5), with the hot flow temperature remaining the same, while the cold flow temperature rises, the amount of flow going through the cold stream has to increase, a consequence of a simple energy balance (equation 12) at the merge, in a similar way as for the PHX degradation cases. However, in the SHX case, the turbine inlet temperature has risen significantly, and the turbine has to increase its work in order to meet the downstream T_{target} . This in turn delivers more work to the compressor and allows it to pump more flow through the cold stream. In this way the SHX degradation case accommodates a greater turbine outlet temperature difference than its PHX counterpart with a larger increase in $\dot{m}_{cold}$.

To move the flow rates as discussed (Figure 9(c)), the TCV closes to reduce the hot mass flow and the PV opens slightly in order to maintain constant overall mass flow (Figure 10(a)). This PV

response is because the TCV, in closing, imposes a backpressure on the PV, and hence the PV has to open (slightly) to compensate (Figure 9(b)). In contrast to the PHX case, the compressor is pumping more flow, clearing any potential backpressure between the PV and compressor inlet.

With fixed ram air flow, the increase in cold mass flow as the fouling increases makes the PHX less efficient, and a small rise in its outlet temperature is the observed consequence, Figure 9(a). The compressor has to pump more mass flow, at a higher pressure ratio, and at a higher shaft speed, resulting in a decrease in efficiency. This all contributes to the temperature rise that is seen before entry to the SHX.

From this it can be seen that there is a big difference between the PHX and SHX degradation cases, all originating with the creation of excess temperature, through degradation, and its location with respect to the ACM. Creating excess temperature upstream of the ACM (PHX degradation case) cannot influence the operating point of the ACM and results in a backpressure affecting the PV. Whereas creating excess temperature between the compressor and turbine of the ACM (SHX degradation case) can be more readily accommodated by the system and the turbine work increase, powering the compressor to flow more mass through the cold stream.

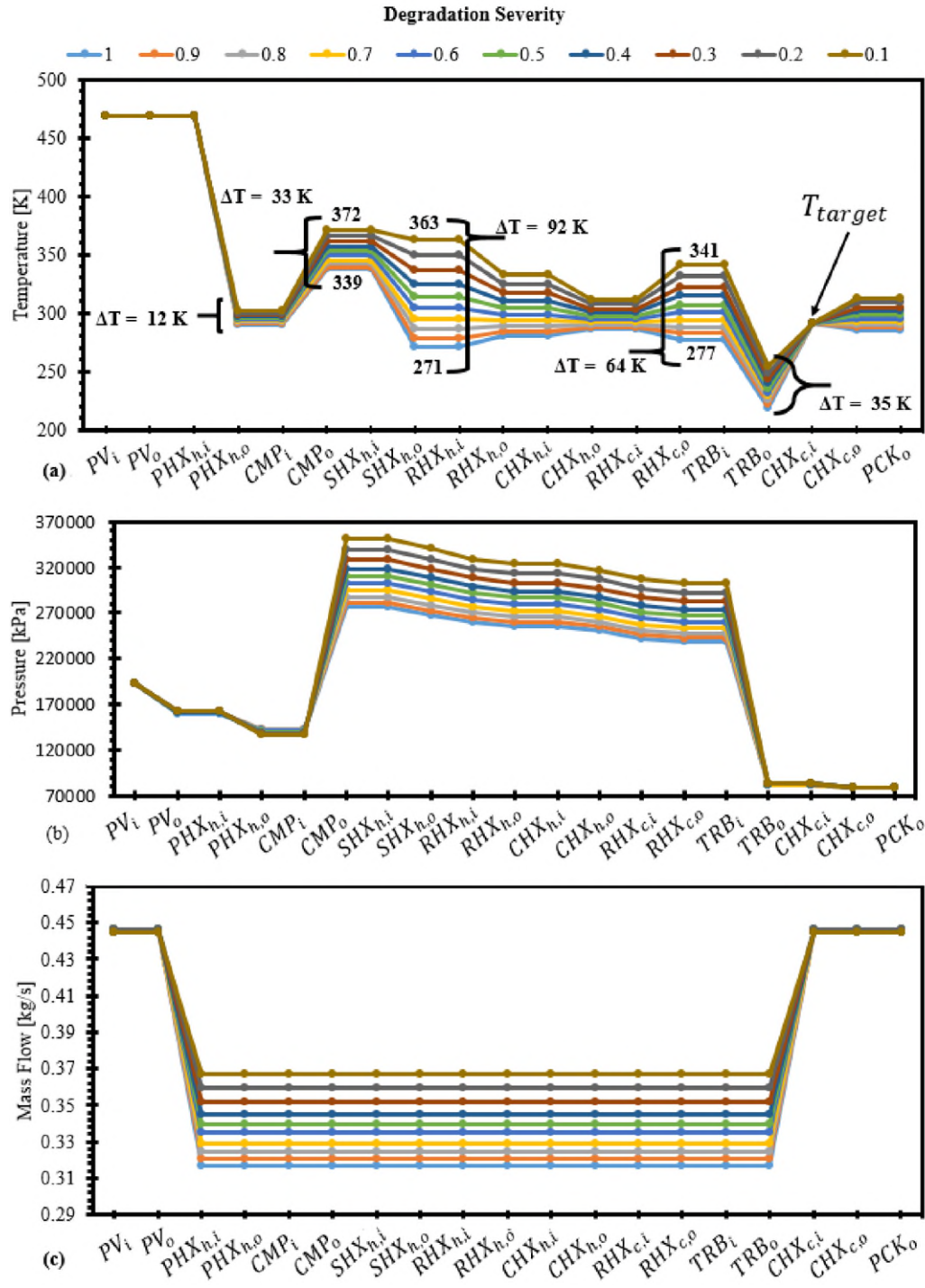


Figure 9. Simulation results for SHX fouling: (a) Temperature, (b) Pressure, (c) Mass Flow.

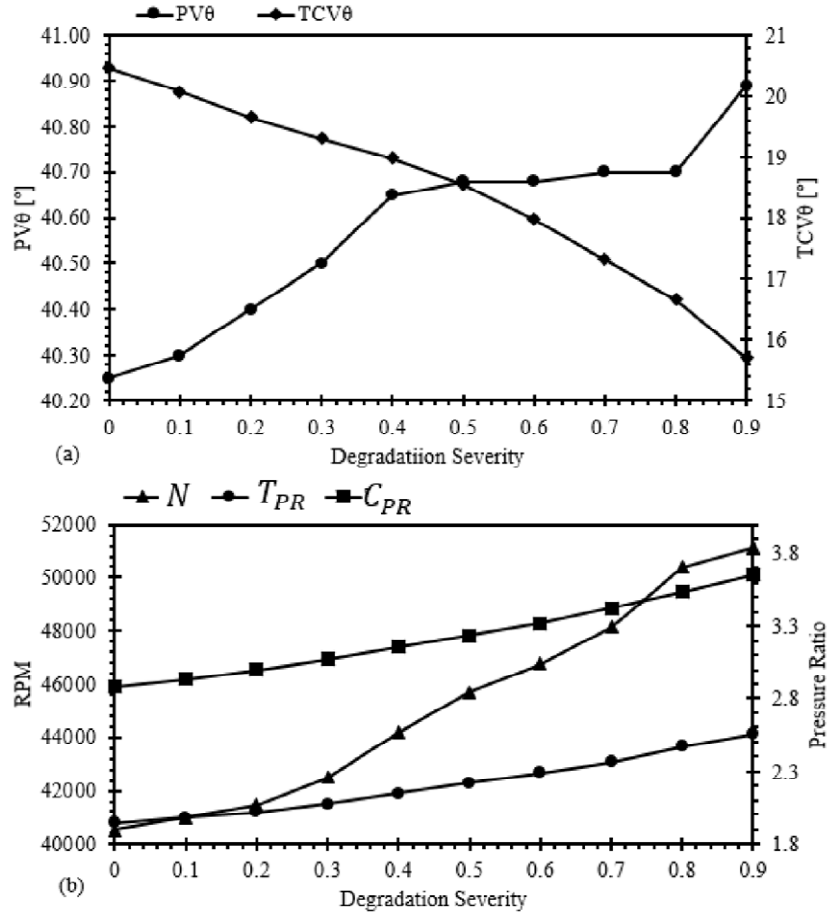


Figure 10. Simulation results for SHX fouling: (a) PV and TCV valve angles, (b) ACM characteristics.

3.3 Ram Air Inlet blockage results

Having discussed the PHX and SHX cases separately, this case now combines the effects felt in both with a restriction of the air flow through the ram. This degradation mode is likely to be caused by an obstruction of the intake by, for example, a bird, tools, or a plastic bag.

The simulation is based on directly reducing the RAI mass flow, corresponding to various degradation severities. RAI serves as a common intake for the PHX and SHX ram inlets, its degradation therefore simultaneously reduces the ram air inlet mass flow for both heat exchangers. Figure 11 presents the temperature, pressure and mass flow throughout the PACK for ram air inlet blockage at various degradation severities.

Through the equivalence of fouling and blockage, discussed in Section 2.3.4, the effects seen for the PHX and SHX in the previous two sections are combined here, and make the narrative considerably easier. The extreme cases (DS above 0.6) will be discussed at the end of this section, after the overall patterns have been established. Starting with the temperature profile in Figure 11(a), the PHX cannot remove as much temperature from the flow as it degrades and hence a large temperature deficit is found at its exit. This is carried through the compressor, increasing due to the increased work done by the turbine, to match T_{target} . The HPWS heat exchangers behave as they did in the SHX degradation case, taking heat from the stream and then putting it back, with no effect of moisture removal as these cases are for dry air.

The turbine outlet temperature variation means the mass flow through the cold stream (Figure 11(c)) has to increase, given equation (12) at the merge, for T_{target} to be met. The TCV has to close (Figure 12) to reduce the amount of hot air bypassing the cooling cycle, and the PV has to open to maintain overall flow against the TCV imposed backpressure (Figure 11(b)). This trend can only continue until the T_{cold} and T_{target} are the same (DS slightly higher than 0.6).

For DS=0.6 the PV is fully open, providing the maximum flow from the engine, while the TCV is almost fully closed, most of the flow being directed through the cold stream. The target mass flow cannot be met, as the turbine work is not sufficient for the compressor to pump any more air. Hence the overall mass flow falls to enable the energy equation at the merge (equation 12) to balance. Once T_{cold} is higher than T_{target} (DS greater than 0.6) then T_{target} cannot be met. This accounts for the temperature profiles in these extreme cases and the corresponding mass flows falling. At this level of degradation the PACK is clearly from away from its design operating point and gross failure would result.

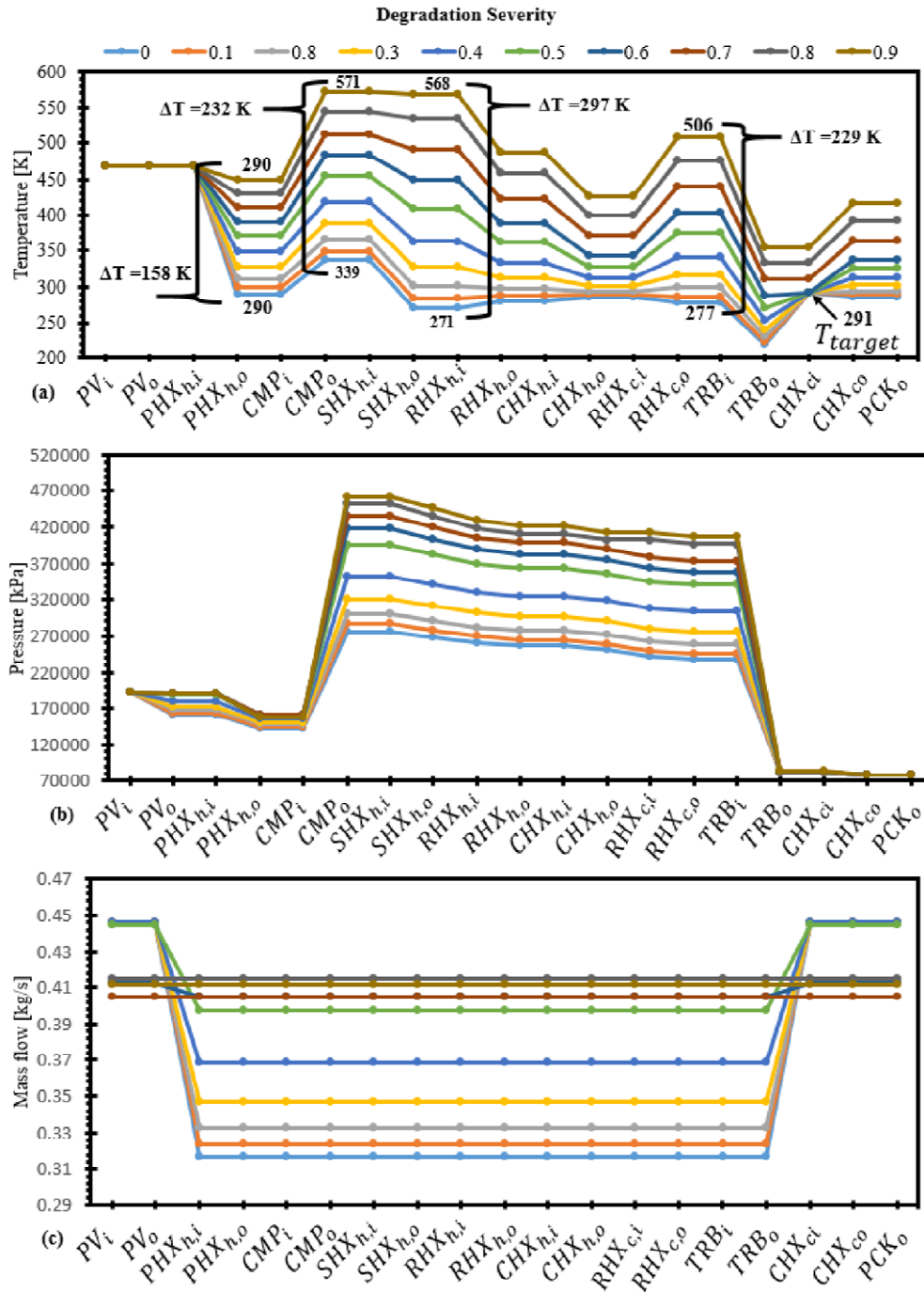


Figure 11. Simulation results for RAI blockage: (a) Temperature, (b) Pressure, (c) Mass Flow.

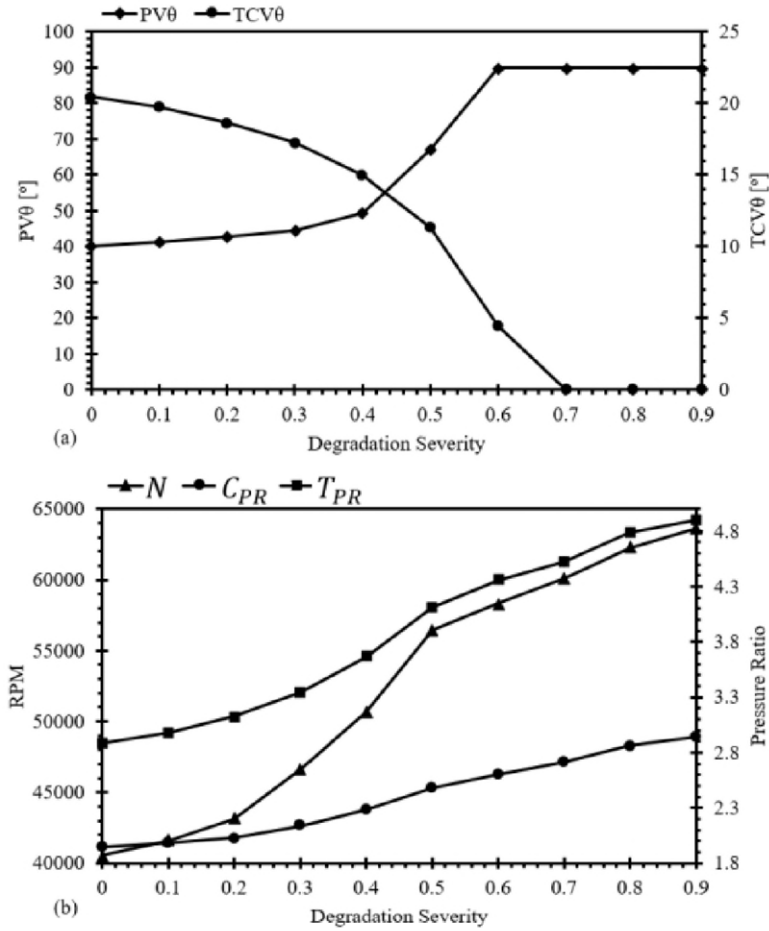


Figure 12. Simulation results for ram blockage: (a) PV and TCV valve angles, (b) ACM characteristics.

4. Summary and Conclusion

In this paper a computationally efficient and cost effective aircraft Environmental Control System (ECS) simulation framework has been implemented to simulate faults in a Boeing 737-800 passenger air conditioner (PACK). A qualitative and quantitative assessment of the critical fault modes associated with the primary and secondary heat exchangers of the PACK has been presented. The simulated fault modes represent blockage and fouling in primary and secondary heat exchangers at various degradation severities.

One learning point was that blockage and fouling, defined as they are in the paper, produce the same results. Further, the effect of PHX fouling is very different to that for the SHX, due to their respective locations in the PACK. PHX fouling results in a backpressure on the PACK valve and very little change in work in the ACM. Whereas, for SHX, the turbine inlet temperature rises and the turbine produces more work, with the compressor responding and pumping more flow; a much simpler scenario. Blockage of the RAI is a combination of these two cases and would have been very difficult to understand had they not been dealt with individually first.

The methodology and findings described in the paper will continue to be extended. Firstly against experimental data being taken on a B737-400, and secondly to produce a robust diagnostic solution for an aircraft ECS.

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