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LEO MÄKELÄ

MODEL-BASED FAULT DIAGNOSIS OF AN AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM

Master of Science Thesis

Tarkastaja: professori Kari T. Koskinen Tarkastaja ja aihe hyväksytty Teknisten tieteiden tiedekuntaneuvoston kokouksessa 9. joulukuuta 2015

ABSTRACT

Leo Mäkelä: Model-based Fault Diagnosis of an Aircraft Environmental Control System
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An environmental control system (ECS) creates habitable living conditions inside an aircraft by pressurizing the cabin, controlling temperature and providing breathing air. This has a major impact on a crew's comfort, performance and safety.

The objective of this thesis was to develop a simulation model of an aircraft's ECS and use it to acquire more knowledge of the ECS's dynamic response. Another area of interest was how modifications affect ECS performance. The project also included comprehensive measurements in order to verify the simulation model.

The thesis resulted in a partially verified simulation model which is valid in some of the most common flight situations. The model still needs further development and thorough testing to increase simulation accuracy and validity. Especially accurate implementation of the dynamic response needs further investigation and research. Despite an unfinished model, we were able to gather new knowledge of the ECS and its characteristics.

TIIVISTELMÄ

Leo Mäkelä: Lentokoneen ympäristöjärjestelmän mallipohjainen vikadiagnostiikka
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Lentokoneen ympäristöjärjestelmä (Environmental Control System; ECS) säätelee hytin paineistusta, lämpötilaa ja tuottaa hengitys ilman. Kaikilla näillä toiminnoilla on suuri vaikutus miehistön mukavuuteen, suorituskykyyn ja turvallisuuteen.

Tämän diplomityön tarkoituksena oli luoda simulointimalli ECS-järjestelmästä ja hankkia uutta tietoa sen avulla. Erityisesti työn aikana pyrittiin syventämään ymmärrystä järjestelmän dynaamisesta käyttäytymisestä. Tämän lisäksi haluttiin tutkia järjestelmään tehtävien muutosten vaikutuksia.

Työn tuloksena saavutettiin osittain verifioitu simulointimalli, mikä toistaiseksi on validi vain kaikkein tavanomaisisimmissa lentotilanteissa. Simulointimalli siten tarvitsee jatkokehittelyä ja kokonaisvaltaista jatkotestaamista, jotta mallin tarkkuutta ja validiutta voidaan edelleen parantaa. Erityisesti simulointimallin dynaamisen vasteen tarkka toteuttaminen vaatii kattavia lisätutkimuksia. Keskeneräisestä mallista huolimatta, projektin aikana onnistuttiin kerryttämään uutta tietoa järjestelmästä ja sen toiminnasta.

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Leo Mäkelä

CONTENTS

ABBREVIATIONS AND SYMBOLS

ACM	Air Cycle Machine	
Bootsrap	The technique of starting with existing resources to create something more complex and effective	
CFD	Computational Fluid Dynamics	
ECM	Electronic countermeasure	
ECS	Environmental Control System	
OBOGS	On-Board Oxygen Generation System	

ϵ	effectiveness	
γ_s	isentropic calorific factor	
γ_T	isotherm caloric factor	
ΔT_c	temperature change of the cold side	[K]
ΔT_h	temperature change of the hot side	[K]
η_{is}	isentropic efficiency	
τ	torque	[N·m]
ω	rotary speed	[rev/min]
ω_c	corrected rotary speed	[rev/min]

A	heat transfer area	[m^2]
C_c	heat capacity rate cold side	[W/K]
C_h	heat capacity rate hot side	[W/K]
C_{min}	heat capacity rate	[W/K]
C_V	specific heat at constant volume	
C_p	specific heat at constant pressure	
dm	mass flow	[kg/s]
dm_c	corrected mass flow	[kg/s]
dmh_{down}	enthalpy flow rate at downstream	[J/s]
dmh_{up}	enthalpy flow rate at upstream	[J/s]
NTU	number of transfer units	
P	pressure	[Pa]
P_r	pressure ratio	
P_{down}	downstream pressure	[Pa]
p_{st}	absolute standard pressure	[Pa]
P_{up}	upstream pressure	[Pa]
P_{rSAE}	pressure ratio	
$T_{c.i}$	cold inlet flow temperature	[K]
T_{down}	outlet temperature	[K]
$T_{h.i}$	hot inlet flow temperature	[K]
T_{st}	absolute standard temperature	[K]
T_{up}	inlet temperature	[K]
T_{1SAE}	inlet temperature	[°R]
T_{2SAE}	outlet temperature	[°R]
q	heat transfer rate	[W]
q_{max}	maximum heat transfer rate	[W]
R_{cold}	thermal resistance at cold fluid level	[K/W]

R_{hot}	thermal resistance at hot fluid level	[K/W]
R_{wall}	thermal resistance at wall level	[K/W]
U	overall heat transfer coefficient	[W/(m^2·K)]
V	specific volume	[m^3]

1. INTRODUCTION

The environmental control system (ECS) of an aircraft is a crucial system for the crew. It pressurizes the cabin, controls temperature, provides breathing air and regulates humidity. Furthermore, ECS is responsible for many other important functions that keep the aircraft fully operational. Like all the other aircraft systems, ECS also has to be robust and reliable in all conceivable situations. It not only affects the comfort and safety of the crew but also the aircraft's capabilities to carry out missions successfully.

The working principle of ECS is very complex. First air is extracted from the jet engines and then directed through series of valves, heat exchangers, a compressor and a turbine. Every single one of these components interacts with others one way or another. Multiple valves constantly regulate temperature, pressure and mass flow. The movement of each valve may have considerable effect on many other valves' movement and unravelling these complex interactions may be impossible for the human mind.

This thesis's ultimate objective is to simulate the dynamic response of ECS during a multitude of different flight situations. A model-based approach provides a new way of studying the behaviour of the system and may improve ECS capabilities even further. Before the simulation model, available methods were merely measurements which are hard or impossible to implement during aircraft flight. Therefore, acquiring the knowledge of ECS conditions were impossible for most of flight situations. Also, before this project, the particular ECS studied was known from experience to be most unstable at high altitudes and the reasons for this could not be tested on ground.

This simulation model is also developed for testing of system failures, effect of modifications and performance in different situations. A simulation model provides an easier and more straight forward method of calculating the effects of varying flight conditions. Without a simulation model, it would be very time consuming and hard to calculate conditions inside the ECS.

1.1 Structure of thesis and methodology

The thesis is divided into three parts. First chapters 2-3 are literature surveys which present the previous studies of ECS simulations and discussion of the ECS at a general level. Secondly chapters 4-5 discuss the modelled system's working principle specifically, and elaborate how the system has been modeled. Thirdly in chapter 6-7, results of testing and verifications of the simulation model are presented and discussed.

Methods used in this thesis were literature surveys, empirical measurements, interviewing, experiments, simulation and computational modeling. Multiple measurements were carried out by the Finish Air Force and Patria. Aircraft cabin pressure and temperature were measured during flight with an *MSR 145* data logger and pressure levels inside the ECS were measured with a ground testing system. Old test data from the aircraft's development process was also partially available. Many stakeholders of this project were interviewed. Multiple highly qualified personnel of the air force were interviewed and collaborated with. Moreover, experiments were carried out regarding a number of unknown characteristics of the system. For example, the movement speeds of cabin pressure regulators were tested in a rig. Similarly, the movement of multiple valves was recorded with a video camera during ground testing. The actual simulation model was constructed with Amesim and verified using all available data.

1.2 Scope of thesis

This thesis focuses only on the core subjects. The literature survey only discusses ECS systems which utilize jet engines, reversed Brayton cycle and bootstrap method. Only a fraction of the different kinds of ECS systems and their implementations can be discussed.

Most of the research is classified and therefore cannot be explicitly discussed. The exact make of the modeled ECS and the aircraft it belongs to cannot be revealed nor their specifications. All figures of the system are simplifications and do not represent a complete system but merely a fraction of it. All classified numeric values are scaled from 0 to 1. Predecessor research conducted by the Finnish Air Forces and Patria is also secret. Moreover, all measurements are classified.

2. LITERATURE REVIEW

Modeling and simulation have been used in aircraft development since the late 60's [1]. First simulation models were just simple representations of single real-word phenomena and gradually developed towards complex multi-domain simulations. Nowadays multiple physics phenomena and their interaction can be modeled simultaneously.

Modeling and simulation have many advantages compared to physical testing. The main advantage is cost effectiveness. Testing of ECS is much cheaper and faster in a computer environment than in physical test rigs. Also, most parts of simulation models are easily adjusted and altered, whereas modifications of physical equipment may be time consuming and costly. [1] Basically, simulation results are a good starting point for the testing of physical equipment. Another reason for modeling ECS is the possibility to test almost anything: simulation testing has no limits and does not require physical components, safety arrangements or test pilots.

Due to rapid computer development, modeling and simulation is now utilized in every aspect of the ECS field. First of all, models are widely used in every development process, since system performance can be tested and optimized easily. Moreover, models are a useful tool for fault analysis and system safety assessment, since a wide range of situations can be tested efficiently. Modeling and simulation provide a cost effective and relatively fast method of research and development.

Steinkellner et al. [1; 2] discuss mathematical modeling and simulation of the JAS Gripen fighter jet. The authors claim that simulation has been an unseparated part of the development process for decades. Modeling and simulation approaches are used for various JAS Gripen systems including its ECS. The most detailed view of the modeling and simulation of an ECS is provided by Karlson. In his master's thesis [3] he presents a model-based diagnosis method for the air distribution system of the JAS39 Gripen ECS. Basically, Karlson modelled an air distribution system and its sensors. He then tested which fault situations could be detected with the sensors available. The result was that 8 situations out of 9 could be detected with the existing system. Karlsson's thesis illustrates well the possibility of modelling usage in fault diagnosis purposes.

Modeling and simulation are used extensively to evaluate the performance of ECS. For example, complex CFD simulations are used to predict cooling capabilities and heat distribution. Aranjo et al. [4] modelled a passenger aircraft cabin and utilized advanced CFD models to evaluate heat distribution. Passenger seats were 3D-modelled and applied to the CFD model's mesh. The model took into account the turbulent flow, convective flow and heat transfer. With this model Aranjo et al. were able to estimate ECS performance and cabin comfort.

Moreover, Leo and Pérez-Grande [5] developed a mathematical model of a passenger aircraft and used it to estimate thermal energy requirements. After the energy requirements were calculated, Leo and Pérez-Grande further calculated the financial costs of the system. Basically, the author evaluated the thermal cost effectiveness of ECS compared to other air conditioning systems.

In a similar way Zilion and Patricelli [6] optimized financial cost-effectiveness of an ECS anti-ice system. The author developed a time-dependent mathematical model and used it to evaluate optimal bleed air flow. In essence the anti-ice system and its effect to fuel consumption were modelled. The authors further compared the model to real-life test results and concluded that the mathematical model represented reality well. Zilio and Patricelli also used the mathematical model to test different controlling methods of the anti-ice system. Ultimately they managed to predict fuel savings achieved by control system modifications.

One of the preceding studies of the Leo and Pérez-Grande [5] & Zilio and Patricelli [6] was Evans' [7] article which examined the direct impact of bleed air to a jet engine's performance. The author used a steady-state mathematical model of the jet engine and estimated bleed air effect on interstage bleed pressure, interstage bleed temperature, net thrust, specific fuel consumption and fan turbine inlet temperature. The results also covered several different flight conditions. The results give a very good estimate of an ECS's overall effect to fuel consumption and thrust. Therefore, these results could be further exploited in cost-effectiveness studies of ECS.

Studies involving the complete ECS system and its dynamic behaviour are hard to find. One could speculate that most studies are done in the context of military-funded classified projects or within major aircraft manufacturing companies. For example, Honeywell corporation announced on June 18, 2007 at the Paris air show that it would lead a consortium which develops new environmental control systems for aircraft, buildings and trains [8]. Yet, public documentation of the project cannot be found, even though one of the objectives was to use "…unique design, simulation and modeling (DSM) tool on air cycle systems…".

In fact only one publicly available study on modeling the complete ECS was found, and it dates back to the middle of the 70's. Eichler studied ECS dynamic response with a computer simulation [9]. The author used IBM 370/165 computers which were sophisticated at the time. Echler developed mathematical models which represented the dynamics of the sensors, controllers, and valves in the system. Echler was then able to calculate the flow rates, temperature, and pressure at various points in the system. With this simulation model ECS performance was tested and compared to the desired specifications.

Even though the articles of the complete ECS and its dynamic response are rare, countless studies of the single components and their responses can be found. For instance, Nakashima et al. [10] studied a pneumatic pressure regulating valve (regulator) and its phenomenon of unstability and resonance. The authors created a mathematical model of the valve and used Runge-Kutta’s method to obtain results. The study showed the correlation between a particular valve structure and unstable behavior. In a similar manner, Garcia [11] studied valve response but focused specifically on the valves’ friction modeling. The author tested eight different friction models and their effect on valve movements. The results were obtained with Matlab Simulink.

In conclusion, there seems to be no compelling reason to argue that mathematical models could not be applied to almost every system related to ECS. Mathematical models and simulation are widely used in optimization, testing and fault diagnosis of ECS. Results of multiple research indicated that mathematical models can be very accurate and useful tools for many different purposes.

3. AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM

This chapter is an introduction to the aircraft environmental control system (ECS). First the fundamental principle of operation is discussed. Secondly an actual physical construction and its design requirements are elaborated. Lastly the most common functions of the ECS are represented.

3.1 Principle of operation

An ECS essentially extracts hot pressurized bleed air from aircraft engines, conditions it and distributes it to the desired location. All this is done by a multitude of components with different functions. Series of valves regulate the pressure, mass flow and temperature. Heat exchangers take part in the cooling process. Water extractors reduce excessive humidity. An Air Cycle Machine (ACM) cycles the air in such a way that effective water extraction and air cooling are possible. All the key components that can be found in almost every ECS are shown in simplified schematic form in Figure 3.1. The system represented in Figure 3.1 has the same principle of the operation as the actual modelled system, but all the values are imaginary and only the general concept of operation is given.

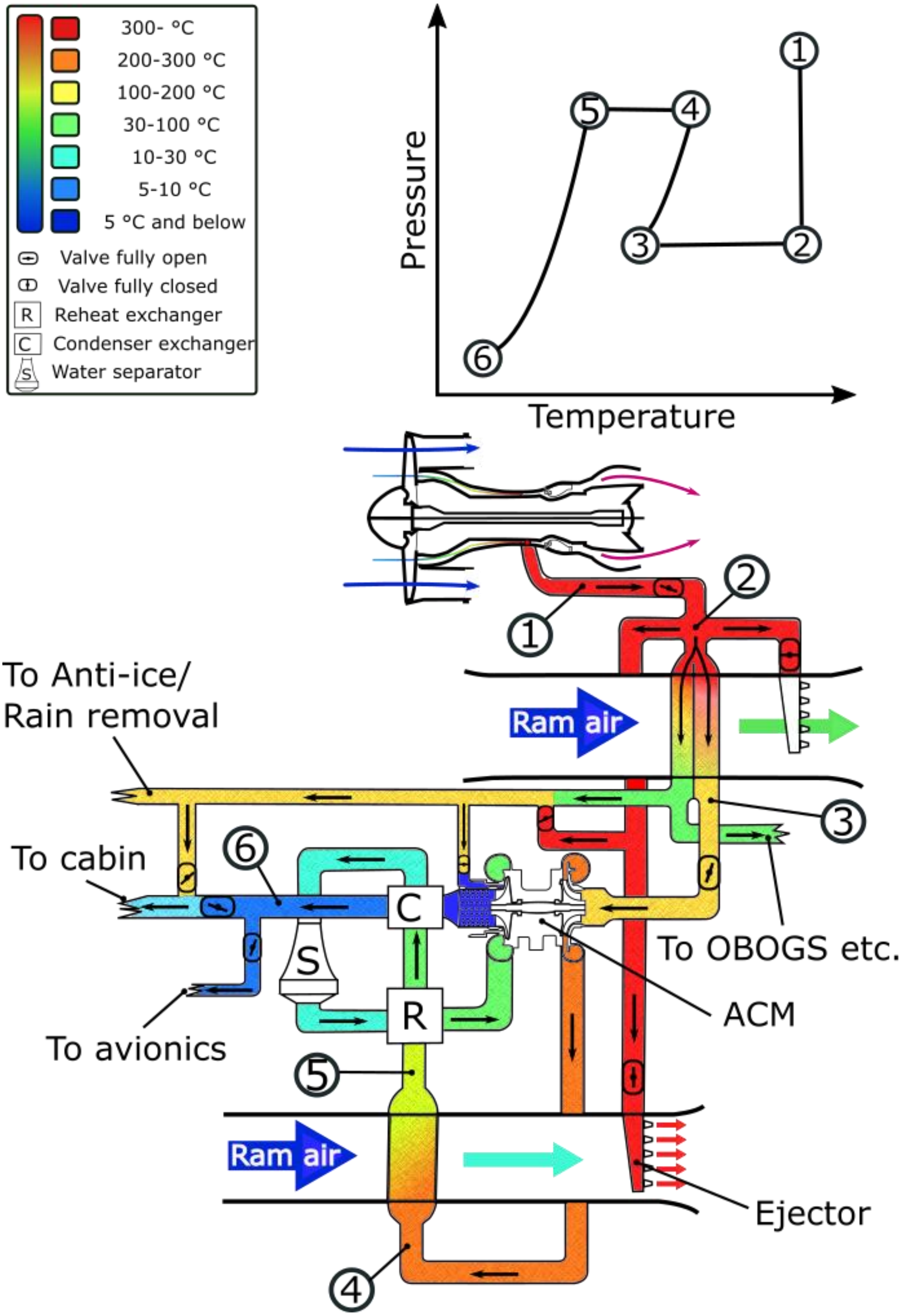

Figure 3.1 Simplified schematic of the aircrafts ECS

First air is bled from the engines and regulated to a predetermined pressure (Figure 3.1 point 1 to 2). Next bleed air is usually cooled against ambient air (ram air) in a primary heat exchanger. Temperature can at this point vary significantly depending on flight conditions and the amount of bleed air. From the primary heat exchanger, warm air can be directed straight to some systems, such as OBOGS and fuel pressurization. But many systems need even cooler or more conditioned air.

Air that needs more conditioning enters the air conditioning package (a.k.a. -pack) which consist of ACM, water separator, secondary-, reheat- and condenser heat exchangers. The air conditioning package can also be called more figuratively as an *air cycle air conditioning system*. In this air cycle system, ACM first compresses the air so that it can be cooled effectively in the secondary heat exchanger (Figure 3.1 point 3 to 4). After the secondary exchanger, air is cooled even further in reheat- and condenser heat exchangers in order to extract excessive humidity. Lastly, air is expanded isentropically through the turbine. It is important to point out that all the exchangers are air-to-air exchangers. Furthermore, air goes through reheat- and condenser heat exchangers twice from different directions.

Air that has gone through the air cycle air conditioning can be used for cooling, or it can be mixed with hotter air in order to produce cabin air. Cold air coming from the air conditioning package is very dry, which makes it ideal for cooling because excessive moisture has a tendency to corrode electronics. The cabin air must also be relatively dry for the same reason. However, the human respiratory tract can get irritated if the breathing air is too dry, which is why a small amount of hot humid air is mixed to it.

In some situations, air gets too cold when it expands through the turbine. This may cause icing of the turbine blades or condenser heat exchanger. Usually icing occurs when ambient air is relatively humid which also increases humidity inside the ECS. Icing can be prevented by allowing hot air flow through an anti-ice add heat valve. In Figure 3.1 and Figure 3.2 a turbine outlet construction is shown into which hot air is directed. The turbine outlet consists of two concentric pipes. The inner one is full of holes that allow the hot air stream to slowly mix with the cold stream. The inner pipe warms up and prevents ice formation or melts ice. Constant hot air streaming is not necessary, because hot air can be added in intervals or when flow resistance rises due to icing.

If an aircraft is not moving or moves very slowly, enough ram air is not available. In these situations, air in the ram air duct needs to be accelerated with the help of ejectors or a fan. Ejectors utilize bleed air in their action and spray an air stream in the direction of the exhaust. This lowers the pressure in the ram air duct and helps to accelerate air flow. Similarly, fans can be used instead of ejectors. In a similar fashion, the fans create lower pressure before them and get the air moving through the duct. Fans are commonly used in passenger aircraft whereas ejectors are utilized in small military aircraft such as fighters.

The air cycle air conditioning process is very complex as almost every single component interacts with each other. For example, if one valve at upstream is actuated, it changes the pressure and temperature levels downstream. Basically the whole situation can be changed by actuating a single component.

When control algorithms are also taken into consideration, the process gets even more complex. A control system is constantly measuring temperatures and mass flow rates, and adjusts valve positions accordingly. When thinking of the over ten valves that are almost constantly actuated, the severe complexity becomes apparent.

Changes inside the actual ECS are just a part of the whole picture. Ambient air temperature and pressure alternate as well. Flight conditions play a major role when the whole aircraft is considered. ECS has to work differently when the aircraft is on the ground compared to when it is flying at cruising altitudes and speeds.

The **Air Cycle machine** (ACM) is an important part of the cooling process. It includes a compressor and turbine on a common shaft (Figure 3.2). The turbine drives the compressor and takes the required energy from bled air. External forces are not required to run ACM, instead hot pressurized air itself provides needed energy for spinning motion. This method which only uses already existing energy to run ACM is called ‘bootstrap’. The effectiveness of the bootstrap method is based on the reversed Brayton cycle. [5; 12]

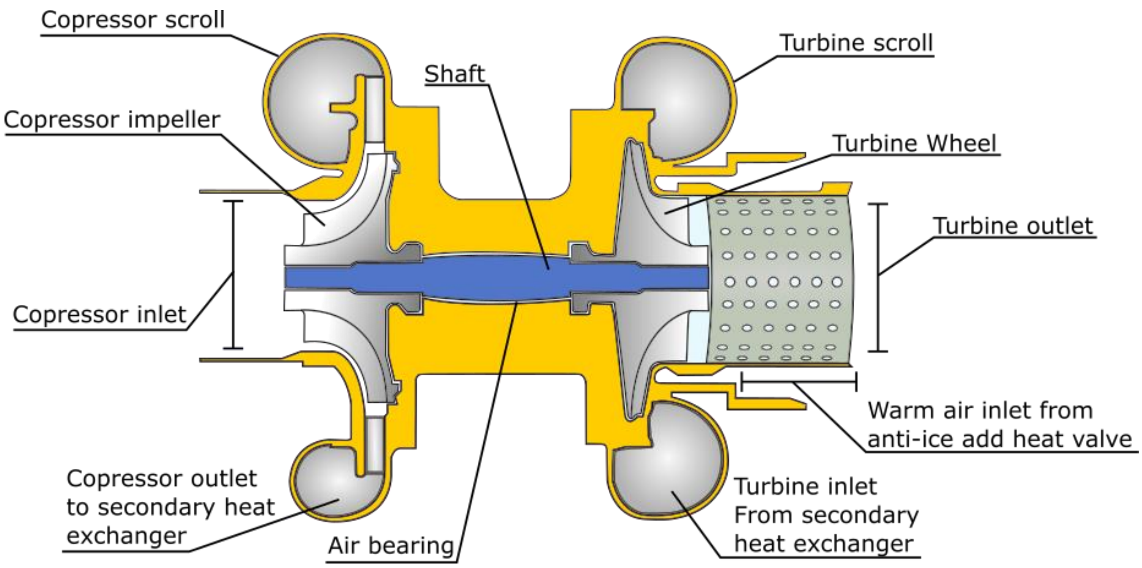

Figure 3.2. Air cycle machine cross-section view (adapted from [13-20])

With the reversed Brayton cycle air can be cooled beyond ambient air temperature. This is particularly important on the ground. For example, on tropical islands where temperatures can be very high, it is not possible to make the air cooler against hot ambient air by using only air-to-air heat exchangers. For that reason, some special methods need to be utilized.

In case of ACM the special method is compression. First, air is compressed adiabatically which increases temperature and pressure. Then it is directed through the secondary heat exchanger. Because of the increased heat after compression, air can now be cooled effectively against ambient air. The greater the temperature difference between hot and cold side of heat exchanger, the greater the efficiency. [21]

Finally air can be expanded through the turbine which decreases temperature and pressure. Air is now cooler than when it entered the compressor. This is made possible by the second heat exchanger that removed energy from it.

Usage of the bootstrap method, described above, has two advantages. First, conditioning air can be cooled beyond ambient air temperature. Secondly, a smaller heat exchanger can be used due to a greater temperature difference between ambient and conditioned air.

Air cycle air conditioning system is not the most effective way of cooling, but on the other hand it is very robust and reliable in addition to being comparatively light and compact. These are all desirable characteristics in the context of an aircraft. [22]

The **Bleed air system** takes advantage of the jet engine's compressor stages in order to produce pressurized air. Typical compressor stages and bleed ports are shown in Figure 3.3. Air is scooped into the engine and compressed with multiple stages of rotating blades. Every stages increases pressure and temperature. [23] Air can then be bled from the engine at a desirable stage. In some cases ECS utilizes two bleed ports at different pressure stages, which makes it possible to choose between two pressure levels.

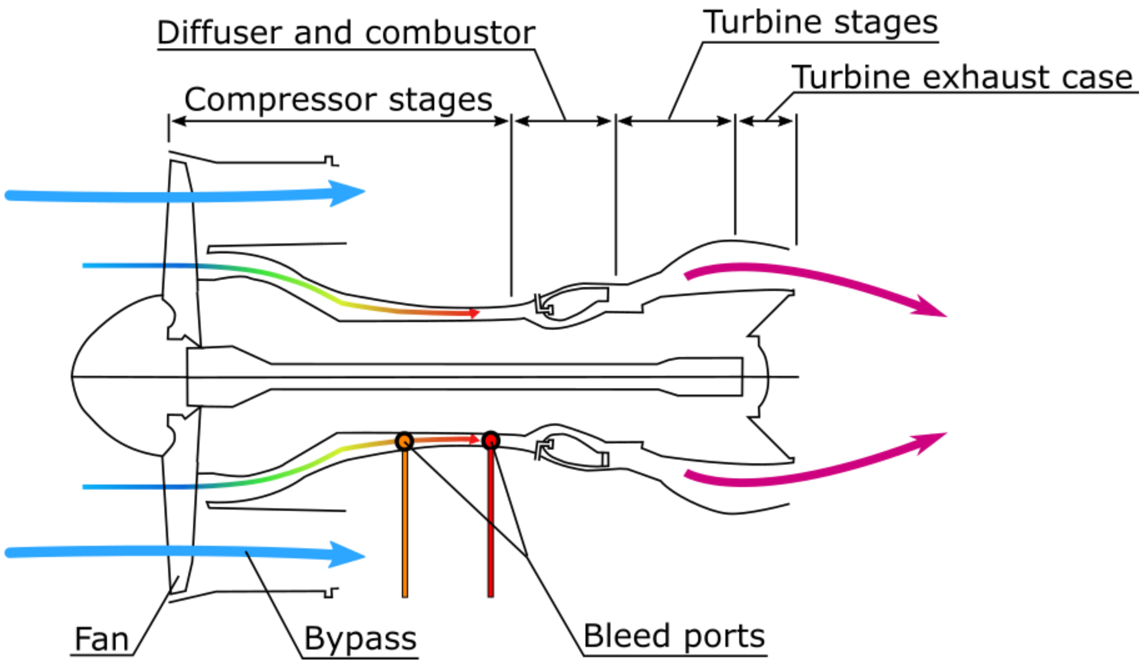

Figure 3.3. Jet engine construction (adapted from [23])

Bleed air pressure and temperature can change significantly during flight. On full throttle the compressor stages are most effective at compressing air. Essentially more produced thrust means faster compressor blade rotation. In addition, flight altitude affects the compression as higher altitudes result in lower pressure inside the engine. Temperature is directly proportional to the compression, and thus higher pressure ratios equal greater temperature changes.

Pressure changes need to be controlled, because ideally ECS supply pressure stays constant. Bleed air valves regulate the ECS supply pressure immediately after bleed ports. Basically bleed air valves only restrict airflow when needed so that pressure drops to a desired level. Occasionally engines cannot compress air efficiently enough to reach the target level and thus ECS supply pressure decreases. This may have a negative effect on ECS operation, since mass flow amount is proportional to the supply pressure.

Some ECS systems contain two bleed ports in order to fulfil mass flow demands in all situations. Primarily air is bled from a bleed port at lower pressure stages and a port at higher pressure stages is only initiated in special situations. If bleed air demand increases suddenly or if engines cannot compress air efficiently, a bleed port at a higher pressure stage is initiated. Usually a twin bleed port solution is utilized in passenger aircraft.

In some cases the engine contains only one bleed port. This might lead to the situation that enough bleed air is not available due to low pressure levels inside engine. These situations occur mainly at high altitudes when throttle position is set to low. Ultimately this may lead to ECS deficiency which will be discussed further in following chapters.

Water separation is quite simple to implement. The whole process is based on the fact that hot air can contain more moisture than cold air. When air is cooled in a heat exchanger, small water droplets start to form in saturated air. [24; 25] Those newly formed droplets can then be extracted by directing the air stream to a swirling motion. In this fast motion those relatively heavy droplets tend to drift to the outer rim where water condenses and coalesces. [26] Eventually water drains to the bottom half, from where it can be collected. This process is shown in Figure 3.4.

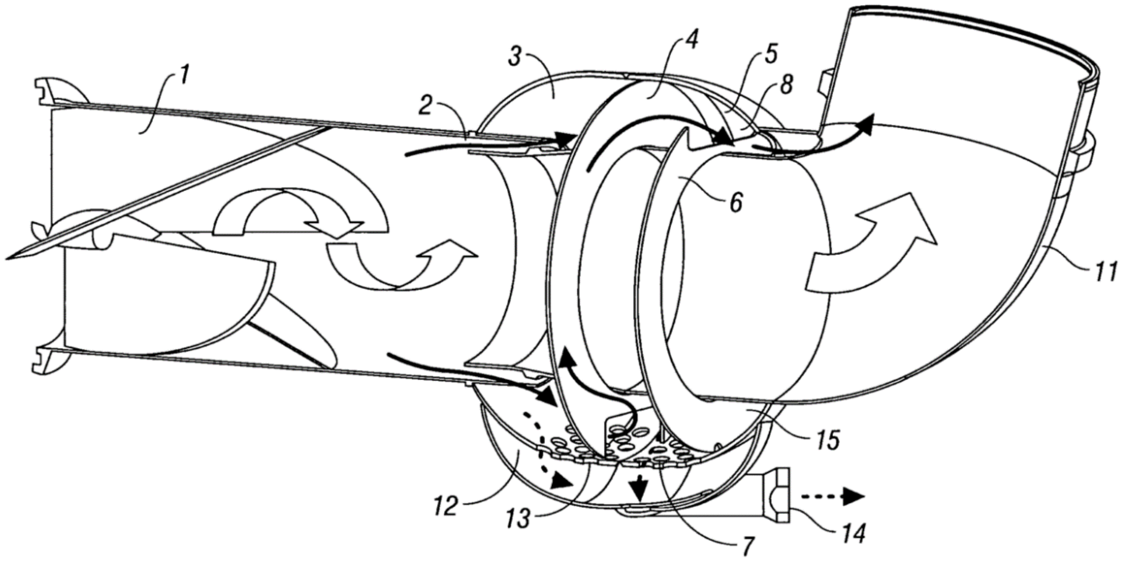

Figure 3.4. Water separators principle of operation [27]

Even though the actual separation process is simple, attention has to be paid to temperature levels. Exceedingly cold temperature leads to icing of the separator or other components whereas hot temperature can reduce the separator's ability to condense water. Moreover, the goal is to control humidity and sustain it at certain level, which can be complicated in changing climate conditions.

Heat exchangers in ECS are almost universally of a cross-flow type. The reason for this is their relatively small size, light weight and easy implementation. Typical heat exchanger construction is shown in Figure 3.5.

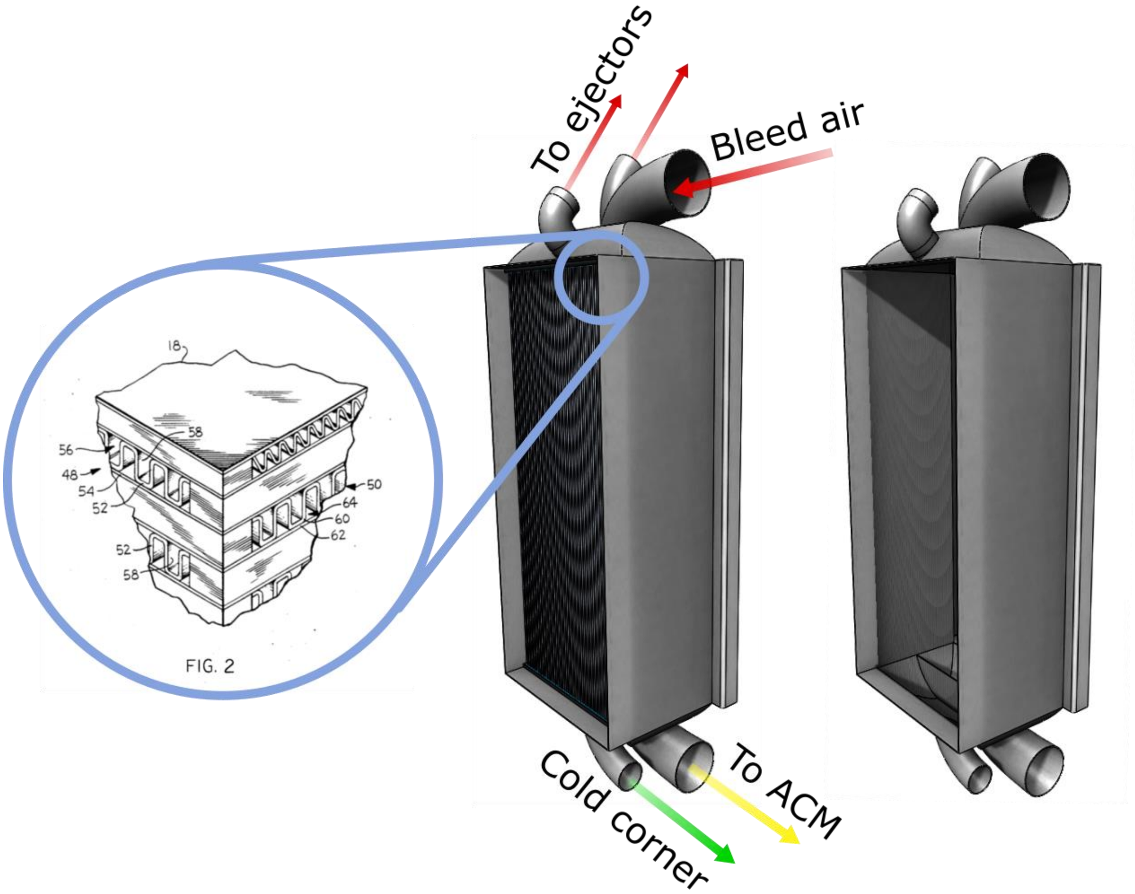

Figure 3.5. Primary heat exchanger of the modelled system (not exact copy) [22; 28]

Even though the working principle is quite simple, there are still some things to consider. For example, in Figure 3.5 the heat exchanger makes use of a so called “cold corner”. It is the part of the exchanger where the coldest air comes out. It is created at the front side of the exchanger where cold air gets in. The front of the exchanger is most effective area for cooling because of maximal difference between ram air and hot air. Energy is transferred most effectively when the temperature gradient is highest.

Moreover, mass flow on both sides and the length of the passageways affect the heat transfer. If we assume that mass flow amounts on cold and hot sides are equal but passageways on the hot side are longer, then temperature changes more on the hot side. This is due to fact that hot air stays longer inside the heat exchanger and thus transfers more energy during the journey through the heat exchanger. Similarly, mass flow rate affects temperature. At this point we consider this only in a simplified fashion: the greater the hot mass flow through the heat exchanger, the hotter the air that comes out from both sides of the heat exchanger. Conversely greater cold mass flow results in a better cooling capability. This is true only to some extent and will be discussed further in later chapters. [21]

To put all of this in perspective, one simple real life situation will now be discussed. There is almost always an excessive amount of ram air (cold air) available. However, every bit of bleed air (hot air) from engines lead to fuel and power losses, hence only the minimal required amount of bleed air is used. Ram air intake also affects fuel consumption by increasing overall drag, but the effect is less significant. As a result, more ram air is vented through the heat exchanger than bleed air. This leads to the shape shown in Figure 3.5 that is flatter towards the direction of ram air. This construction is also necessary because pressure difference over the heat exchanger is smaller in ram air ducts. In other words, pressure losses in ram air ducts inside the heat exchanger cannot be as large, because air must flow through relatively freely. Whereas in the heat exchanger’s hot side, larger pressure losses can be allowed, because pressure levels are much higher to begin with. Yet another reason for a flat shape is the cooling capability which does not increase considerably even if the heat exchanger’s cold side would be longer.

3.2 Physical structure

The physical structure design of ECS relies on and is constricted by the same factors as other aircraft systems. Design has to be relatively light, reliable, robust and easy to maintain. Specific requirements depend on which purpose the aircraft is designed for.

An aircraft’s purpose dictates some of the physical features and forces to use certain solutions. For instance, passenger aircraft has to pressurize a large volume of air, so air packages have to be relatively large. In the same way, military aircraft have their own special requirements that have to be considered.

A **Passenger aircrafts** common ECS layout is shown simplified in Figure 3.6. It is designed to be easily maintainable, fault proof and conveniently located. All these goals can be achieved at once, but some sacrifices have to be made. For example, passenger safety forces the use of two separate air conditioning packs in order to provide a fault proof system. This adds weight and volume to ECS, but ultimately makes the system much more reliable in all situations.

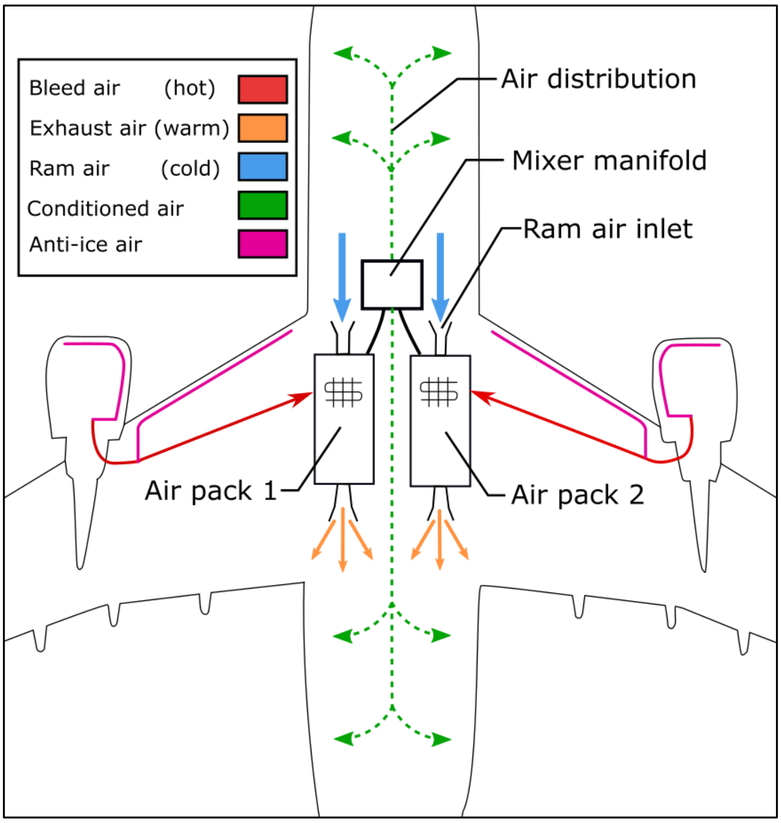

Figure 3.6. Passenger aircraft ECS layout from a bottom view

Maintenance can be easily done from underneath the aircraft. Two air conditioning packs are located at the bottom section of the fuselage and are easily accessible by opening service doors. Most of the components are located in the immediate vicinity of the air conditioning packages which makes most of the repairs and inspections simple [26].

ECS adds weight that has to be considered in order to maintain aircraft controllability. The center of mass has to be in situated correctly in relation to lift force. For example, if air conditioning packs are placed in upper section of the fuselage, they elevate the aircraft's center of mass. Lift force is of course unaffected, but the relation between the two is skewed and this may cause unstable behaviour or poor handling. [29]

Placing air conditioning packs at the bottom section is also advantageous for ram air inlet and exhaust positioning. Ram air ducts are ideally short and relatively straight, so that air flows almost without resistance through them. When we acknowledge the fact that the ECS cannot be on the upper sections of fuselage, the only meaningful positioning for a ram inlet is at the bottom.

A more detailed view of ECS physical structure is shown in appendix A. The figure represents an imaginary ECS and its ducting. Basically, air from air conditioning packs is mixed in a mixing manifold and then directed to the flight deck and cabin. Usually air enters the cabin from the upper section of the fuselage and exits from lower parts of the fuselage. Some of the air might be recirculated or it can be dumped overboard, depending on the ECS system.

Military aircraft often fly in much more challenging conditions. An aircraft's velocity and altitude may change constantly and weather conditions can be challenging. ECS is also utilized to provide a wider range of functions, such as gun gas purge or cooling powerful ECM equipment. These reasons lead to somewhat different design requirements, but the principle of ECS operation remains the same.

One example of military aircraft ECS layout is presented in Figure 3.7. This particular aircraft is chosen as an example because it illustrates perfectly how much ECS requirements might differ. SR-71 is a long-range strategic reconnaissance aircraft. It is the fastest and highest flying aircraft ever manufactured with a top speed of 3.2 Mach and flying altitude up to 85,000 feet. These specs set up an ultimate challenge for ECS design. [30; 31]

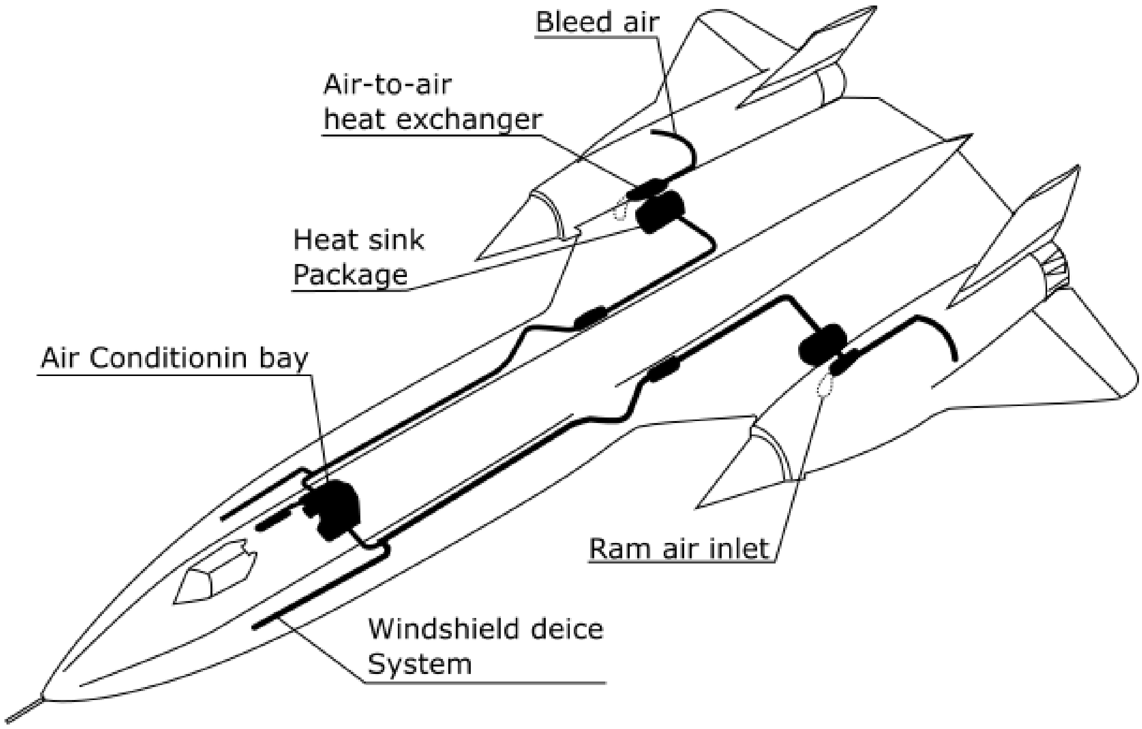

Figure 3.7. SR-71 Environmental control system general layout (adapted from [30; 31])

At such extreme speeds heating becomes a major problem. Surface temperatures at leading edges can rise up to 430 °C and inside the engine nacelles temperatures are even more extreme and peak at a suitably infernal temperature of 666 °C. Moreover, solar radiation also intensifies at higher altitudes. All the phenomena listed above tend to heat up the cabin and other areas inside the fuselage. [32]

All the heat stress makes air conditioning very demanding. Bleed air temperature can rise up to 666 °C and at the same time the ram air which it cooled against is at 400 °C temperature. After the first air-to-air heat exchanger air is still at 440 °C. Needless to say, this cooling against ambient air is not enough. That is why the SR-71 also uses heat sink packages (fuel-to-air heat exchangers) in order to bring the conditioning air temperature down. The first pair of heat sink packages are right after the air-to-air heat exchangers and the secondary packages are located in an air conditioning bay. The ECS also contains two air cycle machines. Cooling is done by two separate air conditioning packages not unlike in passenger aircraft, but because of extreme cooling demand both of them are simultaneously running. [33]

In this particular case, cooling with fuel-to-air exchangers is possible due to huge fuel reserves. The flight mission is also predetermined and extreme cooling is only needed in the middle of the mission when cruising at maximum speed for about an hour [31]. Towards the end of the flight mission, fuel runs low which makes fuel-to-air cooling impossible, but by then air-to-air exchangers alone are sufficient for cooling.

Unlike the SR-71, fighter aircraft flight missions are unpredictable. Top speeds may have to be reached at any given moment in various altitudes. At the same time weather can be hot or cold, humid or arid, whereas cruising altitude conditions are always the same in SR-71 missions. Further, performance of the aircraft or the ECS cannot be compromised, ever. Thus relying on fuel-to-air cooling might not be as beneficial although it is very effective, it cannot be utilized in situations where fuel reserves are low. Alternatively, relatively large air-to-air heat exchangers provide the required cooling capabilities for all situations imaginable.

Every bit of added weight or volume in a fighter aircraft decreases performance. For that reason, ECS is as compact as possible and utilizes only one air conditioning package. Because of this, the system is not as fail safe as in passenger aircraft, but reliable enough. Severe failure of one key component such as the cabin flow valve can compromise the mission at hand, but rarely causes loss of the aircraft and even less often loss of a crew. Fighter aircraft also have backup systems that use ram air instead of conditioned air in case of an emergency.

Altogether, requirements for aircraft in military applications are much more complex and contradictory. Fighter aircraft need to be fast, light and maneuverable, but at the same time need to have as heavy armament, equipment and range as possible. These requirements lead to an ECS that is light weight, compact, robust and relatively reliable. The ECS can handle a multitude of different weather conditions and flight situations. However, one compromise is done as the system does not have total redundancy and might rarely fail causing the abortion of a mission. In such cases aircraft combat capabilities might be compromised, but these very expensive aircraft are unlikely to be lost.

3.3 Functions of environmental control system

ECS has many vital tasks as mentioned earlier. Basically, ECS consists of multiple systems that co-operate with each other. All of these systems must be understood in some extent to fully comprehend the whole environmental control process. May it be noted, that in this short thesis only a fraction of the different implementation options can be discussed. Some of the most important and illustrative functionalities are presented to give a general idea of the ECS. Here is list of some of the possible functionalities:

- Cabin pressurization
- On-Board oxygen Generation System (OBOGS)
- Cooling
- Defog
- Anti-ice/Rain Removal
- Muscle pressure
- Reservoir pressurization
- Anti-G
- Gun gas purge

Cabin pressurization is the one of the most vital tasks. Without it passengers would suffer from severe decompression sickness and suffocate. Long lasting exposure for low pressure also may affect to health, especially if a person is not in optimal condition to begin with. Pressurization also greatly affects traveling comfort and performance of the crew.

Cabin pressure is regulated mainly by a pressure regulator valve. It controls the mass flow rate to the exhaust ducts. When pressure needs to be decreased it is actuated to a more open position, which increases the flow rate out of the cabin. When pressure needs to be increased it does the opposite. Usually a pressure regulator valve independently settles to an optimum position.

If the pressure regulator valve fails or it can not regulate pressure fast enough, a cabin safety valve will assist. Usually the cabin safety valve is set to open if pressure difference between cabin and ambient exceeds a predetermined level or if ambient pressure is greater than cabin pressure (negative pressure relief). The safety valve can be also utilized in some other safety features such as cabin air dumping.

Modern cabin pressure regulator and safety valves often combine pneumatic, electric and electronic control of pressurization. These control systems can vary greatly and use many kinds of methods of control. Because of such variation, only one simple pressure control system is presented. This almost fully pneumatic construction is shown in Figure 3.8 and discussed profoundly in following chapters.

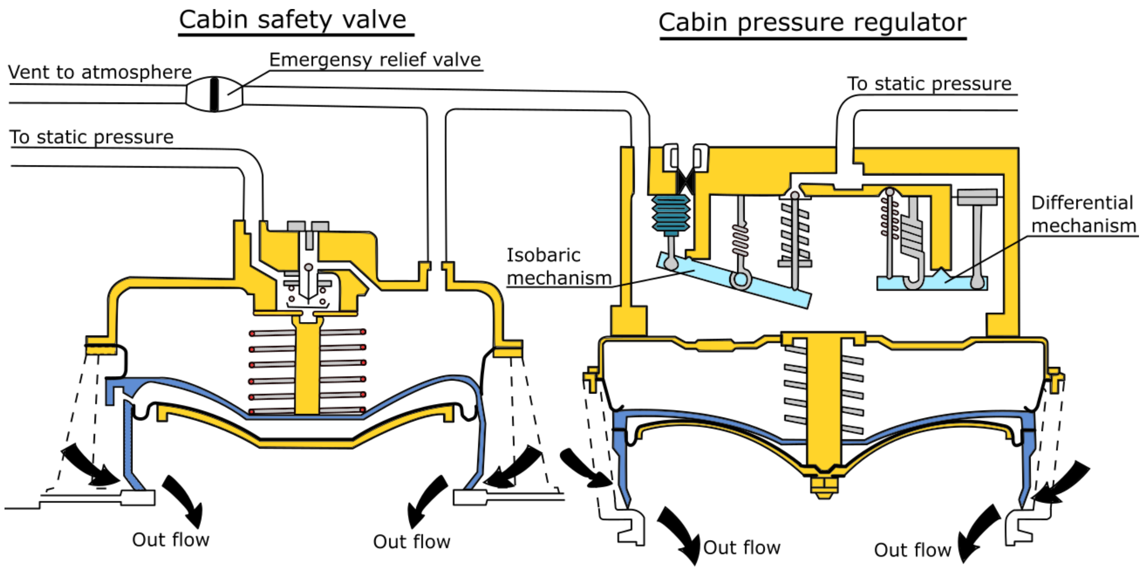

Figure 3.8. Section view of cabin pressure regulator and cabin safety valve (valves shown in closed position)

Cabin pressure can be regulated with two different modes which are isobaric and constant differential. The isobaric mode keeps cabin pressure constant even if flight altitude alters. For instance, in passenger aircraft during cruising, flight altitude can change but cabin pressure stays constant. The constant differential mode keeps the pressure differential between cabin and ambient air constant. Basically this means that when aircraft gains altitude, both ambient and cabin pressure decreases, but pressure difference stays constant. Both of the modes are shown in Figure 3.9 that presents a conventional fighter aircraft cabin pressure schedule.

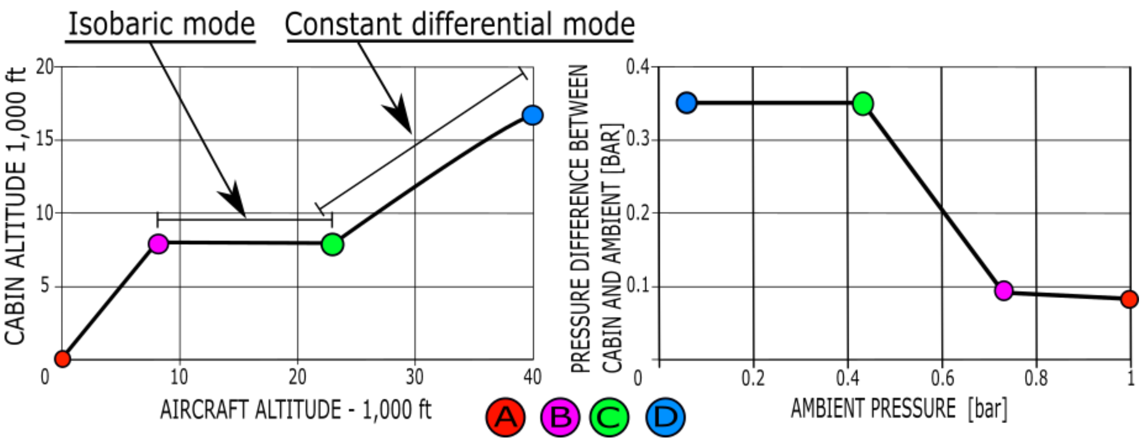

Figure 3.9. Typical fighter aircraft cabin pressure schedule and pressure difference compared to ambient

As seen in Figure 3.9, when the aircraft is at sea level (point A), pressure is slightly higher in the cabin. Even though the pressure regulator is fully open at this point, air rushing to the cabin still causes a small pressure rise. The pressure regulator stays fully open until the aircraft reaches an altitude of approximately 8,000 feet (point B). Then the regulator's isobaric control system is activated. When the aircraft gains further altitude, the regulator moves towards a closed position, which increases pressure difference between cabin and ambient. Eventually pressure difference rises to a preset maximum value and constant differential mode is activated (point C at ≈23,000 feet). From this point forward, cabin pressure decreases and the pressure differential stays constant. Way from point C to D is not straight but a slightly parabolic curve. The parabolic shape can be seen easily in Figure 3.10 which illustrates the change of ambient pressure relative to altitude.

Maximum flight altitude determines the pressure schedule. The higher the aircraft flies, the greater the pressure difference must be, so that absolute cabin pressure does not fall under a certain healthy limit. Additionally, if the crew do not use breathing masks, cabin altitude must be lower in order to provide sufficient breathable oxygen rich air. Thin air makes it harder to deliver enough oxygen it to the brain, even if pure oxygen is added to the cabin air mixture. A key parameter is partial pressure of the oxygen that in an ideal situation stays fairly constant. Lack of oxygen causes symptoms of hypoxia that are described later on.

The pressure schedule in a passenger aircraft differs considerably from the ones used in military applications, as the main focus is on passenger comfort. A conventional pressure schedule is shown in Figure 3.10. Higher cabin pressure makes the journey more comfortable especially during long flights. Low pressure can contribute to swelling of legs, for example. Also like mentioned above, denser air makes it easier for the human body to take up and deliver required oxygen for the brain.

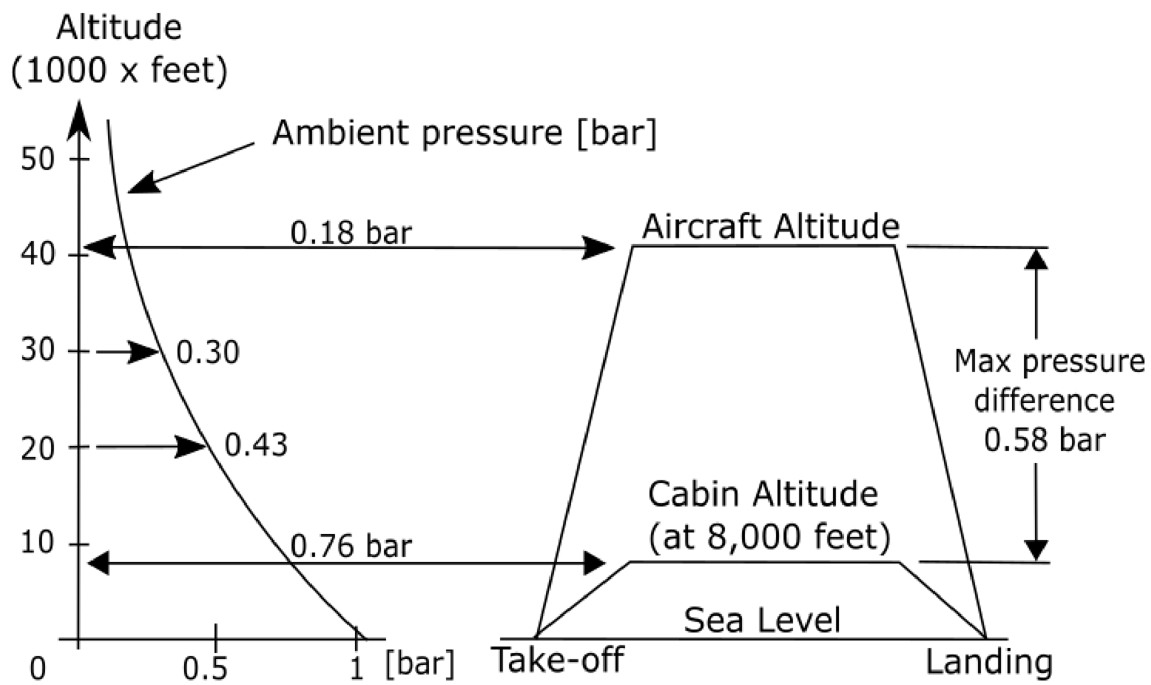

Figure 3.10. Imaginary passenger aircraft pressure schedule during flight at maximum flight altitude (adapted from [34])

When looking closer at Figure 3.10 it becomes evident that the pressure schedule differs quite a lot from fighter aircraft. At take-off the pressure difference between cabin and ambient is nearly non-existent and rises steadily to a maximum value (0.58 bar). Cabin altitude is usually between 6,000–8,000 feet. Basically isobaric mode is not initiated until at cruising altitude. Furthermore, constant differential mode might not be utilized at all. Many kinds of variations do exist, however.

Flight mission are totally different in military and civil aviation which is the reason for totally different pressure schedules. Passenger aircraft for instance always fly from point A to point B as fuel-efficiently as possible and follow a predetermined flight plan. In military missions however, flight altitudes and situations can change constantly. At any given moment, there is a possibility that the pilot is exposed to sudden depressurization. The greater the sudden pressure change, the more severe the consequences. For this reason, pressure difference between cabin and ambient does not exceed a certain limit.

On-Board oxygen generation system (OBOGS) produces oxygen rich air by passing bleed air through a sieve that separates oxygen molecules. Almost pure oxygen can then be mixed with conditioned air in order to increase concentration of oxygen. For instance, in military aircraft cabin pressure decreases considerably at maximum flight altitudes which makes breathing inefficient. If enough oxygen is not transported into the body tissues, hypoxia results.

Symptoms of hypoxia slowly starts to appear at cabin altitudes above 10,000 feet. At 15,000 feet physical tasks feel more exhausting and performing skilled tasks becomes almost impossible. At 20,000 feet physical task are extremely hard, thinking is slow, and calculation ability becomes unreliable. Yet the crew do not notice any difference. Instead they easily become light-headed and overconfident. Even most skilled and experienced pilots are in no condition to fly an aircraft. Above 20,000 feet human start to lose awareness and eventually collapse. If oxygen supply is cut off entirely, awareness is lost swiftly and brain death soon follows in 4 to 5 minutes. [34]

Low partial pressure of oxygen is the most important factor that leads to hypoxia. The higher the partial pressure of oxygen, the more efficient the lungs are at transferring oxygen into the bloodstream. When pure oxygen is added to the air mixture, concentration and partial pressure of oxygen increase. At altitudes up to 33,000 feet, oxygen can be added so that breathing is equivalent to breathing at sea level. Beyond 33,000 feet, even 100 percent oxygen is not enough to raise partial pressure to the same value that it would be at sea level. [34]

In fighter aircraft OBOGS provides extra oxygen so that crew performance is not affected by high cabin altitude. Also in case of sudden depressurization of the cabin, pure oxygen gives more time to descend to a safe altitude. However, if depressurization is caused by malfunction of ECS, it may also affect OBOGS, and that is why in emergencies crew switch the breathing air supply to small emergency oxygen tanks. These tanks are attached to seats and also utilized when using the seats' ejection function. Yet another useful property of pure oxygen is that oxygen decreases the amount of nitrogen in the bloodstream and therefore helps to prevent depressurization sickness.

In passenger aircraft oxygen is added to breathing air only in emergency situations. Typically, these situations are contamination of cabin air or depressurization. Long exposure to oxygen enriched air has negative side effects such as nausea, dizziness, muscle twitches, blurred vision and convulsions.

Cooling is required in the cabin and avionic bays. Cabin cooling is a major challenge in large civil aircraft, whereas in military applications avionics cooling plays a crucial role due to high power radar and electronics systems.

On large passenger aircraft the most demanding cooling requirements occur during on-ground operation. This is caused by hot ambient air that reduces air-to-air heat exchanger effectiveness. In addition, ambient air is hottest on the ground. These problems are dealt with ground cooling fans that blow air straight to the avionics or to other conditioned bays. In the same way, fans accelerate the air flow inside the ram air ducts. Total cooling effects is then adequate for a relatively short ground operation duration.

In the same way military aircraft such as fighter jets utilize ground cooling fans in order to cool avionics and other crucial components. In case of a fighter jet, ram air fans are not always practical and ejectors are used instead. Ejectors are more practical in the middle of a flight because ejectors can be initiated easily. In the middle of the flight ejectors are needed in special situations when ram air flow is decreased due to slow aircraft velocity. Such situations might occur during special combat maneuvers.

In military operations a large demand for cooling can also occur at high altitudes. Very fast flight speed increases ram air temperature and heat caused by friction, and consequently cooling becomes more demanding even though ambient air itself is very cold.

Defog systems ensure good visibility for a pilot in all situations. Fog may appear when windscreens surface temperature falls below the dew point of cabin air. This commonly happens when an aircraft descends from a cold and dry atmosphere to warmer and more humid climate. If the windscreen is warmed up, this phenomenon does not occur. [34]

In fighter aircraft, a defog system usually uses the same conditioned air that is a part of the cabin pressurization. Basically, the air is redirected through defog nozzles which blow straight towards the windscreen. This warms up the windscreen and blows off the already formed fog.

Windshield Anti-ice and rain removal system supplies temperature controlled air to provide airflow over the external surface of the windshield. Hot air flow removes rain droplets and ice. In some cases this system is also called anti-fog system, because hot air prevents fog formation onto the internal surface of the windshield.

Anti-ice systems can additionally refer to other systems that utilize hot bleed air in ice prevention. For instance, in passenger aircrafts ice accumulates onto the leading edges of the wings, and might ultimately lead to loss of lift or jamming of actuators. These potentially catastrophic events can be prevented by melting formed ice with bleed air. [6]

Muscle pressure is basically pneumatic pressure created from bleed air. Figuratively speaking, pneumatic pressure is used as a muscle to actuate equipment. Typical applications are electro-pneumatic-valves in which pneumatic pressure actuates valves alongside electric servomotors.

Reservoir pressurization is an important part of many systems. Pressurization makes pumping of fluids easier and reduces risk of cavitation. Common applications are hydraulic liquid and fuel reservoirs. In passenger aircraft, water reservoirs also need to be pressurized, since adequate hydrostatic pressure cannot be created.

Anti-G systems are used in aircraft with high-g maneuvering capabilities. Basically an anti-G-valve receives either a mechanical or electrical signal during a high-g maneuver, which allows air to flow into special trousers worn by the pilot. Air flows rapidly to bladders that add pressure to pilot’s lower body. This prevents blood from escaping from the brain and rushing to the lower parts of the body. [34]

Gun gas purge simply exploits pneumatic pressure to blow gun gases and some of the heat overboard. Gun gas purge is active during firing and for a while afterwards. During firing the main task is to move gases overboard and after firing to transfer the excess heat overboard.

4. OPERATION PRINCIPLE OF THE MODELLED ENVIRONMENTAL CONTROL SYSTEM

In this chapter the working principle of the modeled environmental control system will be discussed. First, all systems which the ECS consists of are presented to give a general idea of the whole system. Next, all the major functional objectives of the ECS are discussed in separate sections.

Because all of the systems are connected to at least one other system, discussion focuses on the objectives, rather than separate systems. Further, the goal is to understand connections between systems and their interactions. The whole process and its complexity only begins to be understood when all different aspects are presented simultaneously.

4.1 Overview of structure

ECS structure of the modelled system is shown in appendix B. The first figure shows locations of the pressure test ports and the second figure shows all key components. The principle of operation is the same as mentioned in previous chapters: the system utilizes a reversed Brayton cycle and bootstrap method for cooling.

The complete modelled environmental control system is a cluster of 13 systems which are presented in Table 1. The systems cannot be divided into the groups unambiguously, and thus corresponding categorization is always vague. Division of the systems could have been made differently and now only the division presented in the aircraft's technical manual is shown.

Table 1. List of systems, theirs functions and accuracy of the simulation model

System	Function	Simulation model
Bleed air system	Controls airflow taken from the aircraft's engines	Detailed model
Bleed air leak detection	Prevents aircraft damage caused by bleed air leaks	Not modelled
Air cycle air conditioning system	Conditions bleed air	Detailed model
Cabin cooling and defog system	controls and distributes airflow into the cockpit.	Detailed model
Avionic cooling system	Controls and distributes cooling air to avionics.	Detailed model
Cabin pressurization system	Controls cockpit outflow air.	Detailed model
Anti-G system	Controls airflow to the pilot's anti-G suit.	Not modelled
Vent suit system	Controls airflow to the pilot's vent suit (Currently disabled).	Not modelled
Windshield anti-ice rain removal system	Controls airflow to the external surface of the windshield.	Simplistic model
Radar liquid cooling system	Provides cooling for the radar transmitter.	Simplistic model
Canopy seal system	Controls air pressure to pressurize the canopy seal.	Not modelled
Waveguide pressurization system	Controls air pressure to the ECM and radar wave guide ducts.	Not modelled
On-board oxygen generation system	Removes contaminants from engine bleed air and provides an oxygen rich gas mixture for pilot/crew use.	Simplified model

As shown in Table 1, only some of the systems have been modelled. Systems which are left out do not have a significant effect on total ECS dynamics during flight, and therefore including them in the model was deemed unnecessary. In this thesis the emphasis is on systems which have the most significant effect on the system's dynamic behaviour.

4.2 Bleed air system

The basic principle of the bleed air system is as follows. The aircraft's two engines provide bleed air necessary to run the ECS. Then two *primary bleed air pressure regulator and shutoff valves* regulate the ECS supply pressure to a predetermined target level. The *Secondary bleed air pressure regulation and shutoff valve* works same way as the two primary valves, but secondary valve is normally fully open and actuated only if one or both primary pressure regulators fail.

The two *primary bleed air pressure regulation and shutoff valves* are normally closed and energised to open. If a valve's solenoid is de-energised, spring load and pneumatic pressure keeps the valve closed. When the solenoid is energised, up- and downstream pressures influence the valve position. If downstream pressure is too high, it actuates the valve to a more closed position until target pressure is reached. If downstream pressure is too low, upstream pressure forces the valve to a more open position. Downstream pressure (which is also ECS supply pressure), is always kept at a constant target level.

The *secondary bleed air pressure regulator and shutoff valve* is a normally fully open backup valve common to both engines. It intervenes only if the supply pressure rises beyond a normal level and otherwise stays fully open. For example, if one of the *primary bleed air pressure regulator valves* passes too much air through and thus causes pressure to rise, the *secondary bleed air pressure regulator valve* takes over and starts regulating supply pressure. Consequently, the risk of a catastrophic overpressure event is extremely small.

Each *primary*- and *secondary bleed air pressure regulator* is also a shutoff valve. Normally bleed air comes from both engines, but in special situations the pilot can close bleed air intake from one or both engines. Also, the control system may actuate valves to shutoff positions if problems in pressure regulation occur. Shutoff capability is also utilized in engine failure situations, on engine start up and when APU is running.

The *primary*- and *secondary bleed air pressure regulators* are designed so that the effects of almost all failures are limited to either the pressure regulation or the shutoff function, but not both. Basically, when a failure occurs, a valve can still shutoff the airstream or it can regulate the pressure. In extremely rare cases where secondary and primary valves both fail to regulate pressure, a control signal commands all three valves to the shutoff position.

Engine compression has a significant effect on the bleed air system and all other systems downstream. Like mentioned in previous chapter, the engine's rotary speed and air density alter the pressure inside the engine. Therefore, in high altitudes when the engine is rotating relatively slowly, pressure might decrease below the *primary bleed air pressure regulator's* target pressure. This in turn causes the *primary bleed air pressure regulators* to open fully. Despite fully open valve position, ECS supply pressure decreases. Consequently, all the valves inside ECS must be actuated to a more open position so that enough air flows through them. Low supply pressure doesn't necessarily cause other effects than boosted valve opening. But if supply pressure is greatly reduced an avionic ram air scoop may be triggered to open or the ECS's capability to satisfy all the air flow requirements may be compromised.

Ideally supply pressure stays constant and does not fall under the *primary bleed air pressure regulators'* target pressure. If however, supply pressure drops below target pressure, it makes great pressure fluctuations possible. If pressure fluctuates after the *bleed air pressure regulators*, it forces all valves downstream to compensate the fluctuation. This might ultimately lead to unstable behaviour of the system flow, cabin flow and avionic flow control. The control system constantly measures temperatures and mass flow rates to the cabin and avionics. In case of a rapid supply pressure change all the valves involved must react accordingly. Rapid reactions may even amplify pressure fluctuation or cause great temperature changes. Too slow reaction, on the other hand can cause pressure surges. The better the *bleed air pressure regulators valves* keep the supply pressure constant, the easier it is for rest of the system to prevent fluctuations. But if the pressure fluctuation happens below the *bleed air pressure regulators'* target pressure, *bleed air pressure regulators* stay fully open and therefore do not move at all.

At this point it seems that the most problematic situation occurs when pressure rises from a very low level to near the *bleed air pressure regulators* target pressure. When supply pressure is below target pressure and suddenly rise due to throttle alternation, it is hard for all the valves react to the change fast enough. The pressure change is simply so rapid that for a brief moment air flows unhidered all the way to the cabin and avionics. In other words, before the sudden pressure rise all the valves are almost fully open and during the pressure rise the valves do not close fast enough. This phenomenon may be caused by one or several valves.

One possible, although unlikely, scenario is that the *primary* and *secondary bleed air pressure regulators* do not react fast enough and thus may even cause overpressure for very brief moment. And moreover, after a brief moment of overpressure it is possible that the valves are actuated eventually too much towards a closed position which starts pressure fluctuation. We do not have indication of such a scenario happening, but still it is possible that the bleed air system increases tendency of pressure fluctuations.

4.3 Cabin flow control

The objective of a cabin flow control system is to provide steady airflow to the cabin. When airflow is kept fairly constant the *cabin pressure regulator* can easily adjust the cabin pressure. If the airflow rate changes radically in a short period of time, it may cause a sudden pressure change that the *cabin pressure regulator* cannot prevent. Essentially, the cabin flow control only regulates the *cabin flow valve* and keeps the airflow at desired level.

Cabin flow has its own schedule which alters according to flight conditions. Cabin flow is controlled by a function of total air temperature, altitude and defog settings (Figure 4.1). The basic idea is to provide a suitable amount of air to the cabin so that the environment stays pleasant or at least habitable. When weather is very cold, it tends to cool the cabin and when weather is hot, it does the opposite. Heat between the cabin and ambient transfers via the canopy and fuselage. Basically, in extremely cold conditions cabin air flow is increased in order to heat the cabin and in hot conditions to cool the cabin.

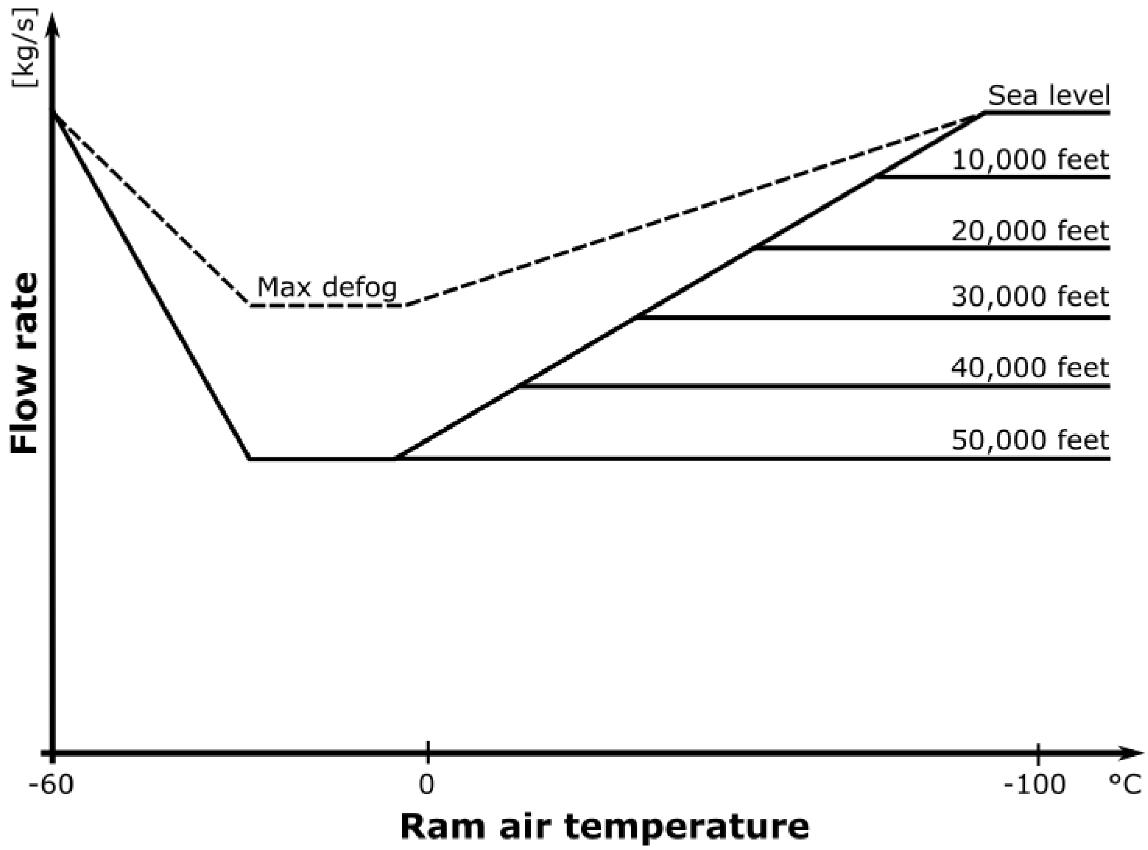

Figure 4.1. Cabin flow schedule

Total air temperature changes according to a function of flight speed, air density and ambient air temperature. Total air temperature (also known as stagnation temperature), is estimated by a measuring device which brings the air to rest relative to the aircraft. As the air slows down and becomes stagnated, the kinetic energy is converted to heat in an adiabatic process. Total air temperature is therefore higher than ambient air temperature. Faster the aircraft velocity, more the kinetic energy is transferred to heat. In the same way, an increase in air density increases the kinetic energy of air. [35]

We are mainly interested in total air temperature since it gives good estimate of the heat transfer between the cabin and ambient air. However, total air temperature is not the only factor in heat transfer. When air gets denser, it transfers heat more efficiently and increases heating caused by friction. So, at low altitudes when air is dense, all the factors together heat up the hull even more than the total air temperature suggests.

Essentially, total air temperature never reaches as high temperatures at high altitudes as at low altitudes. This is also the reason for the curves in Figure 4.1. As can be seen, flow schedule is restricted to certain values at different altitudes.

Altogether, at high altitudes ambient air is cold and thin which decreases the need for cabin air flow. When thin air encounters flying aircraft it causes less drag and therefore less heating caused by friction. Thin air also transfers heat less efficiently. So, at high altitude heat is not transferred via the canopy as much as at low altitudes. Thus airflow to the cabin can be kept at a moderate level. In other words, cabin airflow transports hot air overboard and provides cool air to replace it. Since cabin air is not externally heated considerably, moderate cabin air flow is adequate.

The *Cabin flow valve* plays a major role when the entire ECS's robustness is considered. If the *cabin flow valve* is not working properly, it directly causes pressure surges in the cabin. Ideally an equal amount of air enters and exits the cabin. However, the *cabin pressure regulator* always lags behind when adjusting to a changing situation. Because the *cabin pressure regulator* is very slow in its movements, it cannot keep cabin pressure constant during rapid airflow fluctuation.

To improve the robustness of cabin flow control, the *avionic flow valve* keeps a constant pressure difference over the *cabin flow valve*. Pressure difference over the *cabin flow valve* is very small. In practice this means that even a significant change in the *cabin flow valve's* position does not automatically cause a great change in airflow rate. That makes the flow control over the *cabin flow valve* much more precise. The *Avionic flow valve* also prevents pressure surges. Basically, when pressure suddenly rises upstream of the *cabin flow valve,* the *avionic flow valve* immediately tries to compensate situation by allowing more airflow to the avionic plenum.

Let us now consider the cabin flow control as part of a whole system. Basically, the *cabin flow valve* only tries to keep mass flow to the cabin at a desired level. Simultaneously, the *avionic flow valve* makes sure that pressure over the *cabin flow valve* stays constant which ensures sufficient mass flow to the cabin. Let us now imagine that pressure drops upstream of the *cabin flow valve*, and then the *avionic flow valve* intervenes by actuating to a more closed position. This further causes less mass flow to be directed to the avionics and also causes a pressure rise upstream of the *cabin flow valve*. At this point a *system flow modulating pressure regulator valve* gets a signal that not enough mass flow is directed to the avionics, because the *avionic flow valve* was actuated towards closed position. The *System flow modulating pressure regulator* is then actuated to a more open position, so that the avionics' and cabin's mass flow demands can be met simultaneously. When the *system flow modulating pressure regulator valve* is actuated to a more open position, it increases mass flow and causes pressure to rise upstream of the *cabin flow valve*. Lastly, the *avionic flow valve* actuates to more open position which brings the pressure upstream of the *cabin flow valve* to the right level and increases mass flow to the avionics.

During *avionic flow valve* failure, cabin flow control becomes very challenging. First of all, if the *avionic flow valve* cannot keep pressure constant over the *cabin flow valve*, it also affects the mass flow to the avionics bay. Changes in airflow to avionics further cause the *system flow modulating pressure regulator* to try to compensate the changes in mass flow rates. This might cause the *system flow modulating pressure regulator* to behave unstably and fluctuate its position rapidly. Now the whole system is quite possibly in an unstable situation where pressure levels and mass flow rates are not constant. Ultimately this might make the flow control to the cabin very challenging.

All three valves (*cabin flow, avionic flow and system flow modulating pressure regulator*) only perform one operation, but as a group they simultaneously affect multiple aspects. Cabin conditions are the first priority and most likely during unexpected events cabin conditions are not affected significantly. The most important objective is to ensure the crew's safety and prevent cabin depressurization or pressure fluctuation. Thus the whole control system is designed first and foremost to ensure stable conditions inside the cabin.

4.4 Cabin pressure control

The objective of the cabin pressure control is to regulate cabin pressure and keep it at a desired level. This objective is mainly achieved via the *cabin pressure regulator* whose principle of operation is discussed shortly in the previous chapter. The ECS modelled in this thesis utilizes a fighter aircraft's pressure schedule shown in Figure 3.9. Further, the basic construction of a *cabin pressure regulator* and *cabin safety valve* is shown in Figure 3.8.

The *Cabin pressure regulator* is a fully pneumatic valve with two different modes: isobaric and constant differential. Inside the valve lay two different diaphragms which control the valve actuations. At any given moment only one of the diaphragms regulate pressure. The *cabin pressure regulator* senses ambient air pressure and compares it to the cabin pressure. Diaphragms are the pressure sensing elements which activate the movement of the main body. Ideally the valve's main body settles to a position which allows the right amount of air to flow through.

The *Cabin pressure regulator* is very slow in its movements, but contrarily the actual cross-sectional flow area is large. Thus even a small change in its position causes considerable changes in mass flow. This is why cabin pressure stays at adequate level even when mass flow to the cabin changes. However, in severe failure situations the cabin pressure regulator may fail to regulate pressure fast enough.

The *cabin safety valve* activates only if *cabin pressure regulator* fails to decrease cabin pressure. In other words, if pressure between cabin and ambient air exceeds a predetermined limit, the *cabin safety valve* intervenes and decreases pressure by allowing air to flow through it. The *cabin safety valve* is fully pneumatic and it senses pressure differences with a pressure diaphragm. In the same way as the *cabin pressure regulator*, the *cabin safety valve* is also slow in its movements but cross-sectional flow area is large. Despite the *cabin safety valve's* relatively slow movement, it can reduce pressure inside the cabin very fast.

The only electronic function related to cabin pressure control is the cabin air dump. When the *emergency relief valve* is actuated with an electronic signal. The *emergency relief valve* opens a passageway to the *cabin safety valve's* and *cabin pressure regulator's* diaphragms, thus causing both valves to open. Initiation of a cabin air dump evens out pressure differences between ambient and cabin air in a few seconds.

All in all, cabin pressure is normally regulated without any electronic signals. Valves are reactive in their operation. Airflow to the cabin must stay relatively constant so that pressure is not changed considerably.

4.5 Avionic flow control

The objective of the avionic flow control is to provide sufficient cooling for the avionics bays. Mass flow rate is controlled by the *system flow modulating and pressure regulator valve* which regulates mass flow to the cabin and avionics. The *System flow modulating and pressure regulator valve* only monitors mass flow amount to the avionics and the *avionic flow valve* restrict the flow as much as is needed to keep a constant pressure difference over the *cabin flow valve*. Basically, if the *avionic flow valve* actuates towards a closed position, it increases pressure upstream of the *cabin flow valve* and simultaneously decreases flow to the avionics bay. Decrease in mass flow to the avionics causes the *system flow modulating and pressure regulator valve* to open more so that enough air is passed to the avionics.

In other words, the *avionic flow valve* really only regulates pressure in a way that ensures sufficient flow to the cabin. The *avionic flow valve* is fully pneumatic and receives pneumatic control signals from up- and downstream of the *cabin flow valve*. Muscle pressure augments the pneumatic actuation alongside the pressure signals.

Avionic flow temperature dictates the mass flow amount. The warmer the air, the greater the mass flow amount. Avionic flow temperature is controlled by the *anti-ice add heat valve* which follows its own temperature schedule. At high altitudes avionic flow temperature is very cold and at lower altitudes it is warmer. This is due to fact that air is much dryer at high altitudes and therefore does not cause icing of the components. At low altitudes the *anti-ice add heat valve* keeps temperature over water's freezing point so that the condenser heat exchanger or the ACM's turbine do not accumulate ice.

In other words, the *anti-ice add heat valve* controls the avionic flow temperature and the *system flow modulating pressure regulator valve* adjusts to the situation by increasing or decreasing the mass flow amount according to avionic flow temperature. If the *anti-ice add heat valve* increases flow temperature, the *system flow modulating pressure regulator valve* increases mass flow. In case of a temperature fluctuation the whole system may start to fluctuate, since the *system flow modulating pressure regulator valve* is constantly trying to adjust to the changing temperature.

Avionics cooling is enhanced by directing part of the exiting airflow from cabin to the avionic bay. *Cabin exit air valve* prevents air escaping overboard and instead directs it to the avionic plenum. *Cabin exit air valve* keeps pressure after *cabin pressure regulator* high enough level that air flows to the avionic plenum. Essentially, it only monitors pressure after *cabin pressure regulator* and adjust its position accordingly. The air that *cabin exit air valve* prevents to go past it flows to right avionic bay and avionic plenum. Air that go through *cabin exit air valve* goes to left avionic bay. *Cabin exit air valve* follows its own pressure schedule which is dependent on the ambient air pressure.

In some unusual situations aircraft engines fail to produce sufficient mass flow for the ECS. This may lead to situation in which avionic cooling must be done with ram air. If pressure before *system flow modulating pressure regulator valve* drops under certain limit or if pressure difference over the valve is too low, it initiates avionic ram air servo. Ram air servo opens ram air scoop which allows air to flow straight to the avionic plenum.

Avionic flow control also contains separate avionics deficiency override circuit which is initiated under extremely low flow conditions. Avionics deficiency override circuit is designed to prevent large pressure surges which may appear during unregulated ECS supply pressure. Basically ECS supply pressure is unregulated when bleed air pressure decrease under *primary bleed air pressure regulators* predetermined target pressure. In other words, when *primary bleed air pressure regulators* are fully open and do not restrict the bleed air flow. During avionics deficiency override circuits action *system flow modulating* *pressure regulator valve* dampens ECS supply pressure changes. Only *system flow modulating pressure regulator valve* is actuated with deficiency override circuitry. When unregulated air supply pressure drops, there will be a corresponding drop in avionics flow rate. The control circuitry attempts to compensate pressure drop by commanding valve towards open position and under extremely low flow conditions valve is commanded to open fully. Further, deficiency override circuitry receives constantly valves position signal and if valves opening exceeds 85 percent of maximum, it commands it to almost closed position. However, valve cannot close in extremely low flow conditions because it requires greater pneumatic signal to operate. Valve starts to move towards close position eventually, after when unregulated air supply pressure increases yet again. Normal control action is restored after valve shortly closes.

4.6 Temperature control

Temperatures are controlled by: *Warm air temperature control valve*, *flow/temperature limiting anti-ice modulating valve*, *anti-ice add heat valve*, *cabin add heat valve* and *system flow modulating pressure regulator valve*. In addition, *primary*- and *secondary ejector shutoff valves* affect to the temperatures and *anti-ice/rain removal pressure regulator and shutoff valve* prevents windshield from overheating.

The *Anti-ice add heat valves* objective is to control avionic flow temperature and prevent icing of a turbine as well as condenser heat exchanger. The control system measures avionic flow temperatures constantly and adjusts valve position accordingly. Control system follows predetermined temperature signal which alters according to altitude. The *Anti-ice add heat valve* also gets pneumatic signals from the pipe between turbine and condenser heat exchanger. If pressure rises due to icing, it increases pneumatic pressure signal and forces valve to open. When ice melts it brings pressure inside the pipe to the normal level and therefore moves valve to its normal operation position.

Anti-ice add heat valves temperatures and pressures may vary at any given moment at both upstream and downstream of the valve. This may lead to constant movement of the valve. Pressure change affect to the airflow through the valve. Similarly, the temperatures changes affect to the needed airflow rate. Occasionally valve could be fully closed, but consistently it is opened considerably.

Cabin add heat valves only objective is to control cabin supply airs temperature. Control system receives temperature signal from a supply pipe before cabin. Temperature is set at desired level chosen by pilot. Pilot can choose air temperature from cold to warm.

Cabin add heat valves control is robust, hence *cabin flow valve* keeps airflow almost constant and *anti-ice add heat valve* temperature almost constant. However, when *cabin add heat valve* opens, it increases flow to the cabin and then *cabin flow valve* must react to it by reducing airflow. In other words, cabin flow amount is sum of a flows through the *cabin flow valve* and the *cabin add heat valve*. Control system only measures the total amount of air that is passed to the cabin. Thus, it is possible, that rabid *cabin add heat valves* movement causes unstable behaviour.

Route from bleed air ports to the *cabin add heat valve* is relatively straight which makes pressure surges possible. In the shortest route, bleed air first bypasses primary heat exchanger and then goes through two valves (*Warm air temperature control valve*, *flow/temperature limiting anti-ice modulating valve).* If bleed air pressure rises suddenly, in some situation, it may affect straight all the way up to *cabin add heat valve*. Since all the valves before *cabin add heat valve* can almost be fully open, pressure surge can have significant effect. Even if *warm air temperature control valve* is fully closed, pressure can still affect from all the way from bleed air ports to the *cabin add heat valve*. Moreover, pressure losses are much lower, when compared to route through air cycle air conditioning. Further*, flow/temperature limiting anti-ice modulating valve* is during a normal operation always fully open and thus does not increase pressure losses considerably. When all the factors are considered, *cabin add heat valve* may cause pressure surges in the cabin.

Things get even more complex and speculative when *cabin add heat* and *avionic flow valves* interaction is considered. It might be that excessive flow through *cabin add heat valve* increases pressure significantly in a pipe where cold and warm flow mixes. This is the same pipe from where *avionic flow valve* gets one of the two pneumatic signals. In other word, excessive flow from *cabin add heat valve* may increase pressure which in turn affects to the *avionic flow valve* and actuates it to more closed position. This further increases the airflow rate through the *cabin flow valve*.

But the question at this point is, how and how fast every single valve reacts to this situation. Flow through the *cabin add heat valve* increases airflow and temperature. If temperature rises it causes the *cabin add heat* valve to restrict airflow. However, if simultaneously flow increases through *cabin flow valve*, temperature rise is not as high than otherwise. At this point has to be kept in mind, that *cabin flow valves* objective is not met, and too much air flows to cabin. Eventually *cabin flow valve* will restrict airflow as does the *cabin add heat valve*. While this speculation goes on, *system flow modulating pressure regulator* is increasing the air flow because avionics do not get enough air. And this causes the second event, in which all the valves are involved. What is going on when this excessive flow reaches *cabin flow* and *avionic flow valve* and what will happen. At this point interactions between these valves are not yet known completely.

Warm air temperature control valve controls the air temperature in windshield/rain removal ducts. It essentially keeps the temperature over predetermined level. This valve affects to the pressures and temperatures upstream of *cabin add heat* and *anti-ice add heat valve*. *Warm air temperature control valve* might be fully closed or opened considerably.

Flow/temperature limiting anti-ice modulating valve controls the temperature in windshield/rain removal ducts. The valve is normally open during system operation and is modulated towards closed position only if over temperature situations occurs. Most likely over temperature occurs during anti-ice/rain removal operation, because hot air flow through primary heat exchanger is then utmost.

System flow modulating pressure regulator prevents ACM's compressor and turbine from overheating. The valve is modulated towards closed position, if temperature rises above predetermined temperature. When flow rate is reduced temperatures decreases.

Primary- and *secondary ejector shutoff valves* are responsible for the ejectors operation. These normally closed valves are actuated towards open when the ejectors are needed. Essentially, these valves are opened during ground operation and when aircrafts velocity is under predetermined limit. Ejectors pump air through the ram air ducts and therefore help to increase primary- and secondary heat exchangers cooling capability. *Primary ejector shutoff valve* may also be open when windshield anti-ice or rain removal function is initiated. This gives a maximum cooling effect and prevents anti-ice rain removal duct from overheating.

4.7 Manual-mode operation

Normally ECS runs in auto-mode and manual-mode is only used as a backup. Failure of the one key component may cause auto-mode failure which forces to change to manual-mode. For example, failure of the cabin temperature sensor, makes the cabin temperature control impossible. But in manual-mode temperature sensors are not needed and temperature is controlled manually by the pilot.

In manual-mode control system basically stops modulating certain valves and keeps them in fixed position. When manual-mode is initiated *system flow modulating pressure regulator* and *cabin flow valve* are actuated to predetermined partially open position. Similarly, *cabin add heat valve* is actuated to fixed position. Essentially, in manual-mode control system does not follow flow or temperature schedules. Instead all the necessary valve modulations are done with fully pneumatic valves, only exception is *anti-ice add heat valve* which works same way as in auto-mode.

For example, cabin flow is controlled only by *avionic flow valve*. It continues normal operation and keeps the pressure difference over *cabin flow valve* constant. Ideally pressure difference stays constant which in turn keeps mass flow to the cabin constant. Essentially, everything works almost as in auto-mode.

However, large pressure surges from jet engines inevitably cause minor airflow fluctuations to cabin flow. *Avionics flow valve* reacts very fast to pressure changes, but in order to keep the pressure difference perfectly constant, it would have to be infinitely fast.

Because *system flow modulating pressure regulator valve* is set to fixed position (almost fully open), mass flow amount to air conditioning cycle changes proportionally to ECS supply pressure. Basically, when the supply pressure increases, the mass flow increases. The mass flow amount may change considerably, especially during throttle alternation. And because valve is almost fully open, mass flow can be very high, even much higher than during auto-mode operation.

Pilot can adjust cabin temperature with continuous control knob, which controls the *cabin add heat valve* position. If temperature knob is set to full-cold *cabin add heat valve* is fully closed and when it is set to full hot, valve is fully open. Temperature control knob can easily be set to desired position, but the actual desired position may change frequently. For example, when throttle is at idle, pleasant temperature knob position is quite near full-hot, but if throttle position is changed to full, pleasant knob position changes considerably towards full-cold.

In manual-mode mass flow amount in air conditioning cycle is considerably higher than in auto-mode. Because mass flow amount is not regulated, valves must be at position which ensures sufficient mass flow in all situations. This means that valves must be kept almost fully open so that mass flow is sufficient even if ECS supply pressure is low.

5. CONSTRUCTION OF THE SIMULATION MODEL

The model is constructed with *LMS Imagine.Lab Amesim* (version 13). Amesim is a mechatronic simulation software for model-based systems engineering. Amesim can be utilized to model, simulate and analyse multi-domain controlled systems. The software provides a wide range of component libraries which can be utilized for ECS modeling. Essentially, all the components needed are ready to be implemented and only parameters have to be resolved.

Amesim was chosen because it enabled all the desired aspects. Firstly, all the necessary phenomena could be modelled accurately enough. Secondly, with Amesim construction of the model is very fast and possible errors are easily avoided. Thirdly, only the constructed model of the ECS needs to be verified, since Amesim's individual components from the component libraries are verified by the Amesim software developers. Fourthly, an intuitive user interface makes the complex troubleshooting relatively easy and fast. Lastly, all the results are easy to share with clients, since the results can be presented numerically, as a graph or with a multitude of visual representations.

A block diagram representation of the complete simulation model is shown in appendix C and all the utilized submodels are shown in appendix D. Let us consider first the model in a simplistic way. We can say that each submodel is a mathematical representation of its real-world counterpart such as a butterfly valve. The complete model also contains so called supercomponents which appear as singular symbols in the block diagram but are actually comprised of multiple submodels. Be noted that only a part of the model's true block diagram can be seen in appendix C.

5.1 Bleed air system

The model of a bleed air system is shown in Figure 5.1. One can imagine air entering the ECS from the left and flowing to the right. First, the air encounters *primary bleed air pressure regulators* which modulate pressure to desired level. Then two airstreams unite in the Y-junction and continue a journey to the *secondary bleed air pressure regulator*. Lastly, air continues towards primary heat exchanger.

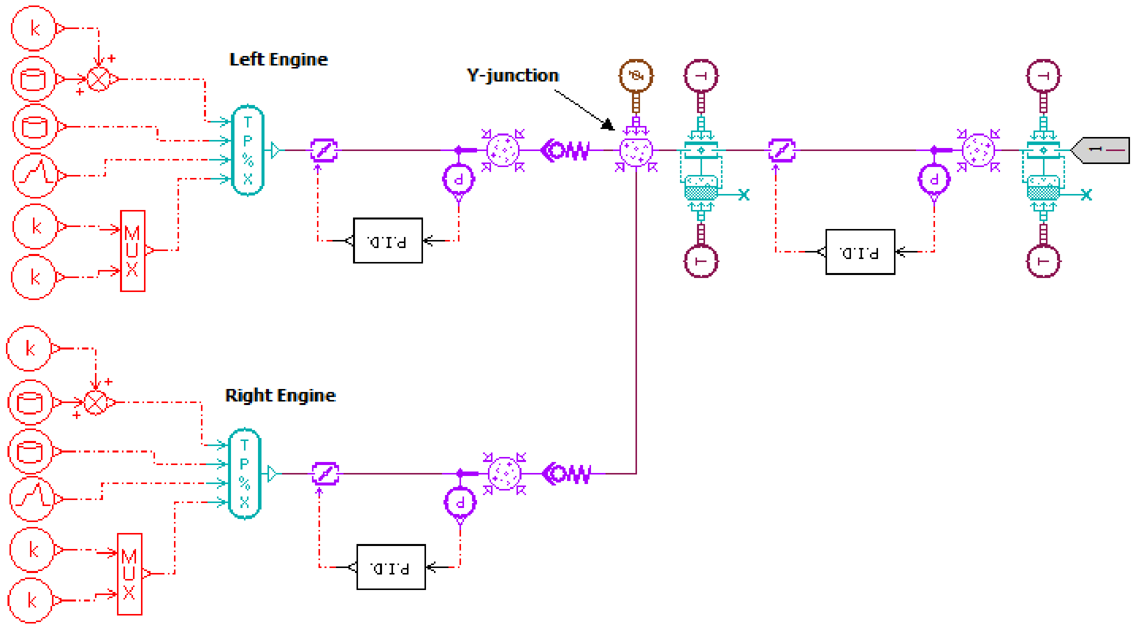

Figure 5.1. Amesim block diagram of the bleed air system

To accurately model the *primary bleed air pressure regulators* effects to ECS, three inputs from the aircrafts engines are needed: temperature, pressure and humidity. These inputs can be precisely estimated from a real flight data stored into an aircraft's flight recorder. Basically, input values change dynamically during the simulation and represent very accurately reality.

Essentially, if we are interested in what happened during a flight, all the measured values from test flights can be used as an input. We can then simulate the situation and look how the input values affect to the environmental control process. It is also possible to alter ECS working principle and then estimate the outcomes of modifications. For instance, the effects of flow schedule alternations can be estimated.

In some cases the measured data from a real flight does not exist. In that case aircrafts engines need to be modelled in order to get a realistic input values. At this point engine model is under development and for that reason some imaginary flight situations cannot be tested accurately. However, input values for static flight situation can be calculated easily. But if input values change consistently, even hundreds of values need to be calculated, what is impossible in practice. For example, if we are interested in rapid throttle alternation, accurate model of engines is needed in order to get reliable results, since temperatures and pressures change constantly.

It can be stated that the bleed air model gives very accurate results only if measured data from real flights are used as an input. Many circumstances have an effect to the bleed air temperature and pressure, therefore, in some cases it is impossible to estimate input values without measurements. For example, let us imagine we want to investigate what happened during the flight and what could have been the reason for avionic over-temp-warning. In such simulation cases, bleed air pressures and temperatures must be correct and these values can be correct only if flight speed, ambient air pressure, ambient air temperature and engines rotational speed are known. Otherwise input values are estimated using ISA-standard atmosphere-model which may differ from real values significantly.

At this point one of the design aspects is the models simplicity in order to decrease simulation time. For this reason, only some of the pipes are modelled. Most of the time, the pipes before and after the *primary bleed air pressure regulators* do not have a significant effect, thus they are left out. Also, it was noticed that when unnecessary pipes were removed simulation stability increased.

However, bleed air model with simplified pipe-models does have serious drawbacks. Because pipes after *primary bleed air pressure regulator valves* are not modelled, pressure losses are lower than in real-life. These pipes are relatively small and cause noticeable pressure loss when mass flow is large. Pressure loss is significant especially during the idle power descent. Even more so with windshield anti-ice selected and single engine operation. To put the point in another way, models accuracy decreases when mass flow increases. Accuracy suffers even more when pressure is low and primary pressure regulation valves are fully open. Particularly, one engine operation gives inaccurate results, because mass flow is then the highest in one pipe and therefore the pressure loss is the greatest.

If the valves modulate pressure to the target supply pressure, then simplified pipe-model has no effect, since pressure entering to the primary heat exchanger is not affected. However, *primary bleed air pressure regulator valves* position is slightly different from what it would be if all the pipes were modelled. In simpler terms, now the pressure coming from bleed air system is realistic when engine produces high pressure, but the valve positions are not. The difference in valve position compared to reality can be considered negligible.

Summing up, simplified pipe-model have a significant effect to accuracy when only one engine is used and particularly so when anti-ice or rain removal are in operation. Inaccuracy is increased even more if engine produces low pressure and the *primary bleed air pressure regulator valves* are fully open. Also because pressure losses are not modelled ideal way, valve positions do not represent realistic values, but are still very near reality. When pressure entering the ECS is very low, *primary bleed air pressure regulators* are fully open and do not modulate airflow. In that situation air flows freely to primary heat exchanger. Now, because pipes from which air enters the ECS are not modelled, pressure loss is smaller than in reality. However, tests with simulation model suggested that most of the time difference can be considered negligible.

Another effect of the simplifications is that air enters the modelled system either from the left or the right engine, not both. This is due to the fact that if pressure after the check valve is higher than before it, check valve closes instantaneously. Basically, the situation could be imagined as higher pressure wins. In practice, if pressures from left and right engine are very close to each other and fluctuate rapidly, engine from which air flow comes from may change several times in one second period. This is because airflow does not have any inertia and is very simplistic mathematical representation. Airflow basically can be imagined to accelerate instantly. The only thing that effects on the mass flow amount is the pressure differential over components and it can change instantaneously. But all in all, it does not matter from which engine the air comes from as long as the pressure stays in a realistic value. If realistic behaviour of the airflow would be modelled, it would require much more complicated pipe-models which considers inertia of the air and also a more complicated model of the check valve. At this state a realistic model would only increase simulation time and sources of error.

In reality air can flow from one or both engines simultaneously. Though, it is almost impossible to know what exactly happens. Next multiple scenarios and their effect are discussed.

If flow resistance is very small throughout the entire ECS, then airflow comes from both engines, because pressure in space after check valves do not rise. Basically, air pressure required to change flow direction back towards engine does not exist. Check valve closes when pressure downstream rises higher than pressure upstream. Pressure itself does not close the check valve, instead airflow that changes flow direction pushes check valve towards closed position or spring pulls valve to the closed position when mass flow is decreased enough.

In practice there is always flow resistance, because multiple valves restrict airflow and therefore causes pressure rise upstream of the ECS. Most of the time pressure after *primary bleed air valves* is near target supply pressure. Now, if the *primary bleed air pressure regulators* modulate pressure to different values, pressure is higher either left or right side. This may lead to the situation, in which the higher pressure forces the check valve in lower pressure side to close. In simpler terms, if pressure on right side is higher it may force left sides check valve to the closed position and then all the bleed air is coming from the right engine. However, pipes after the *primary bleed air pressure regulators* are small related to pipe after Y-junction. So when mass flow amount increases significantly also pressure loss through these small pipes increases considerably. This means in practice, that the pressure difference between left and right even out due to increased pressure loss in the pipe that has a greater mass flow. Presumably, bleed air comes from both engines if *primary bleed air pressure regulator valves* modulate pressure approximately to the same value.

Most of the time engines produce so high pressure that primary *bleed air pressure regulator valves* modulate the pressure to target value. It can be stated that these two valves are never identical and therefore modulate pressure to slightly different value. Further this means that the pressure after valves is higher either the left or the right side. Essentially, either left or right side has a tendency to bleed more air from the engines.

When mathematical model of the bleed air system is considered, it does not matter from which engine bleed air is coming from. Thing that matters the most, is the ECS supply pressure and temperature, hence these values affect to rest of the system. Now the pressure after bleed air system should be accurate and behave in the same way as in reality. But, bleed air model may give slightly too high values when *primary bleed air pressure regulators* are fully open.

5.2 Air cycle air conditioning system

The model of air cycle air conditioning system takes into account all the major physics phenomena which occur in the air conditioning process. All the valves are modelled and they react to changing pressures and temperatures accordingly. For instance, the *system flow modulating pressure regulator* monitors avionic flow amount and modulates mass flow accordingly and also prevents ACM from overheating. Similarly, the rest of the valves act as in real system. Complete model of an air cycle air conditioning system is illustrated in Figure 5.2.

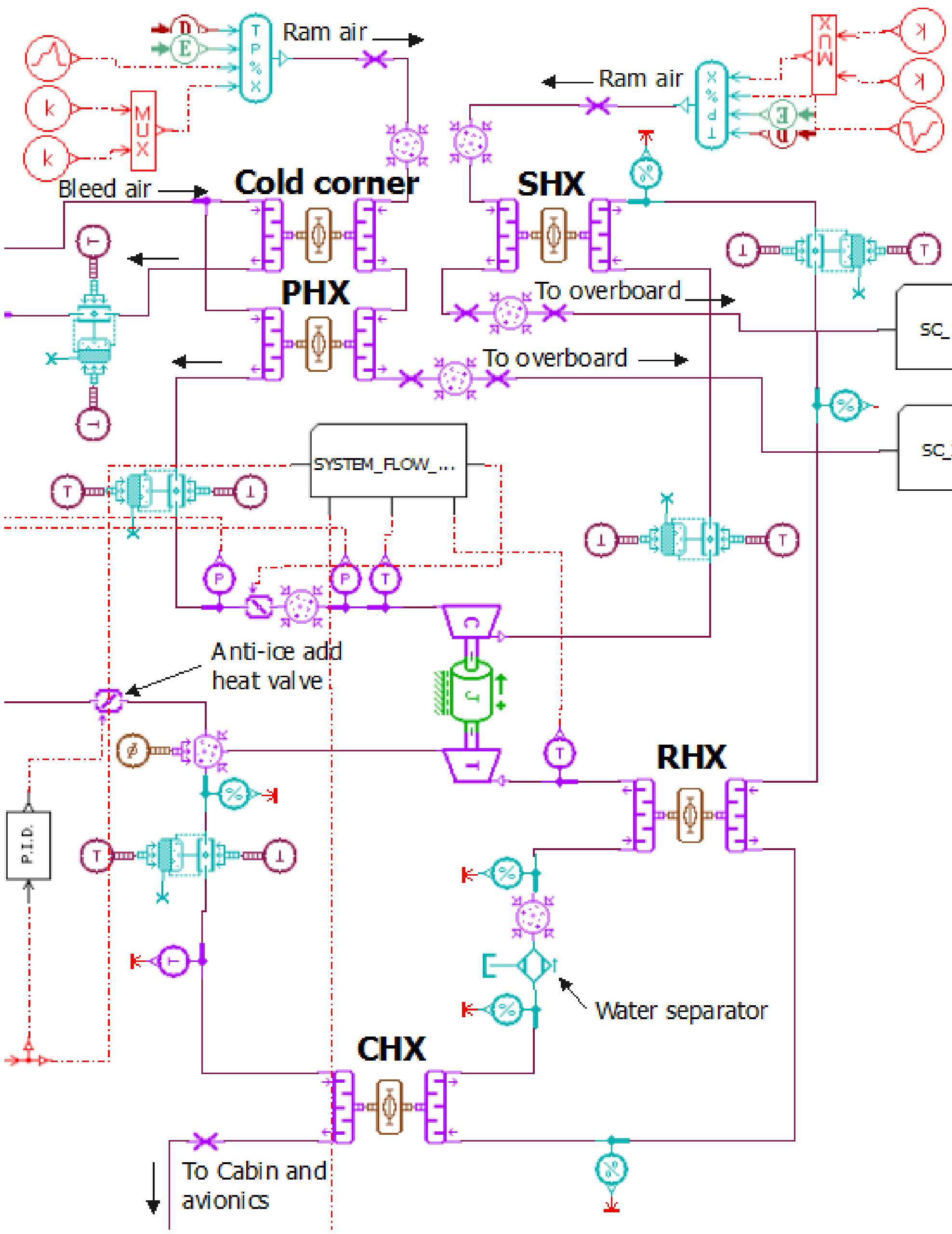

Figure 5.2. Block diagram of the air cycle air conditioning

As can be seen in Figure 5.2, bleed air enters the system from top left corner, goes through the air conditioning cycle and exits from bottom left corner. Also part of the conditioning air comes from the anti-ice add heat valve. Notice that primary heat exchanger is divided into two separate parts so that part of the flow bypasses the air conditioning cycle and goes to the anti-ice/rain removal ducts and for fuel pressurization.

The water separator model essentially extracts a certain amount of moisture from the air and then drains extracted water to imaginary tank [36]. In reality drained water is then injected to the secondary heat exchangers ram air duct. Water drain and injection can be easily modelled, but results are not verified yet.

Water separator have a significant effect to humidity during the air conditioning process. Humidity has a further effect on all temperatures which in turn affects to multiple components. Moreover, conditions inside the air conditioning cycle affect to separators efficiency. However, during a normal operation the water separators efficiency stays almost constant.

Pipes are modelled by using the Amesim's Moist-air-library components. These pipe-models are specifically designed to the modeling of moist air mixtures. Phase changes between water vapor and liquid water are taken into account. Also, thermal exchanges associated to phase changes is considered. Since phase changes occur constantly during air conditioning process, these phenomena must be considered. [36]

5.3 Ram air

Model of a ram air duct is very simplistic and does not consider the effect of multiple phenomena. For example, effects of transonic or supersonic speeds are left out as well as diffusers effect to fluids speed and pressure. Modeling of the actual physical phenomena would have been almost impossible and computationally very demanding. Even though model does not take into account real-world phenomena, it gives good results. Next, discussion focuses first on ram air ducts physical construction, then fluid mechanics and lastly why simplistic model is adequate.

The ram air duct is shown in Figure 5.3. It comprises inlet hole, diffuser, heat exchanger, upwards curved outlet duct and ejector assembly. Inlet hole is relatively small, about a size of a hands palm. Immediately after inlet is diffuser which expands duct to the size of the heat exchangers cold side. After the heat exchanger, duct gets a bit narrower and curves upward. Ejectors are almost at the very end of the exit duct. Lastly, after ejectors, fins change flow direction more towards aircrafts back.

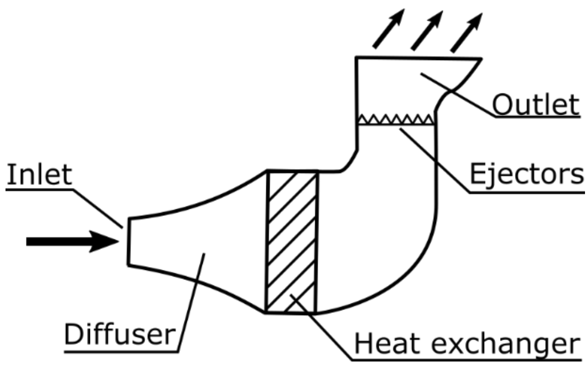

Figure 5.3. Ram air duct

Flow inside the ram air duct is always subsonic, even when aircraft is flying well over speed of sound. Supersonic flow inevitably slows down right before ducts inlet. Transformation from supersonic to subsonic happens always very rapidly, in other words during very short distance. During this transformation static pressure, density and temperature increases. This very narrow region where velocity drops below supersonic is called a shock wave. Thickness of the shock wave is in fact ten-thousandths of a millimetre. [37]

Former Aalto University aerodynamics professor Jaakko Hoffren was shortly interviewed during this thesis project. He suspected that in this particular aircraft, airflow may be subsonic even before inlet. When supersonic flow moves next to a surface that has corner in it, oblique shock wave appears. Oblique shock waves similarly decrease flow velocity to subsonic region. Fuselage possibly causes oblique shock waves considerably before ram air inlet. Inlet is near fuselage which increases a probability of oblique shock waves forming before it. In fact, ram air inlet is separated from fuselage only as much that boundary layer does not affect on the intake.

Ram air flow is modelled simply with restrictions which emulate ram air duct intake and exhaust. Basically dynamic pressure affects to the intake and static pressure to the exhaust. The greater the difference between dynamic pressure and static pressure the greater the mass flow through ram air duct. Dynamic pressure increases when aircraft velocity increases while static pressure represents ambient air pressure. Ram air temperature is estimated with total air temperature. Also real measured values can be used for temperature.

Further, the effects of angle-of-attack and pressure recovery are left out from the model. Ram air intake is shaped so that after a small intake, ram air duct expands before heat exchanger and converges after heat exchanger. Basically, when air enters the expanding duct its velocity decreases and pressure increases, but the total mechanical energy stays constant. This is a very useful phenomenon, because it reduces air velocity considerably before the heat exchanger. Also the intakes expanding shape improves flow characteristics and especially increases mass flow during steep angle-of-attack.

Now the ram air model is kept as simple as possible. Ram air flow could be modelled by using Amesim's CFD-libraries which utilizes CFD-calculations and gives more accurate results. CFD is however a very time consuming method, hence it requires much computing power. [39] At this point very accurate CFD calculations are not used, because current model gives a very good estimate of the mass flow.

Despite the models simple construction, model is computationally demanding. Now relatively large restrictions are combined with relatively small air volumes which lead to long simulation times. Even so, simulation runs considerably faster than CFD model would.

Addition to computation problems, this modeling method does have other weaknesses. For instance, air inlet temperature is the same as total air temperature (stagnation temperature). The total air temperature most certainly gives too high value compared to reality since only some of the air velocity transforms to heat. The whole process involving compressible flow is very complicated to estimate accurately. For example, diffusors pressure recovery factor alters when mass flow rate changes and mass flow rate is affected by even more complicated fluid mechanics. Pressure recovery factor basically tells how efficiently fluids velocity is transformed to pressure and the value of this factor alters significantly function of the aircrafts velocity and angle-of-attack. Theoretically, accurate modeling could be achieved, but it would require immense amount of work and expertise.

5.4 Heat exchangers

Amesim utilizes Number of Transfer Units (NTU) Method in all heat exchanger calculations. Accurate results with NTU-method requires knowledge of the effectiveness of heat exchanger. Now the models of heat exchangers are based on real measured data. During the aircrafts development Northrop Grumman Corporation did measure heat exchangers effectiveness and its relation to the mass flow amounts. This data is used to accurately model heat exchangers in Amesim. Basically, during simulation, hot and cold mass flow values are used as an input for effectiveness table which then dictates the effectiveness value. The effectiveness table of a secondary heat exchangers is shown in Figure 5.4.

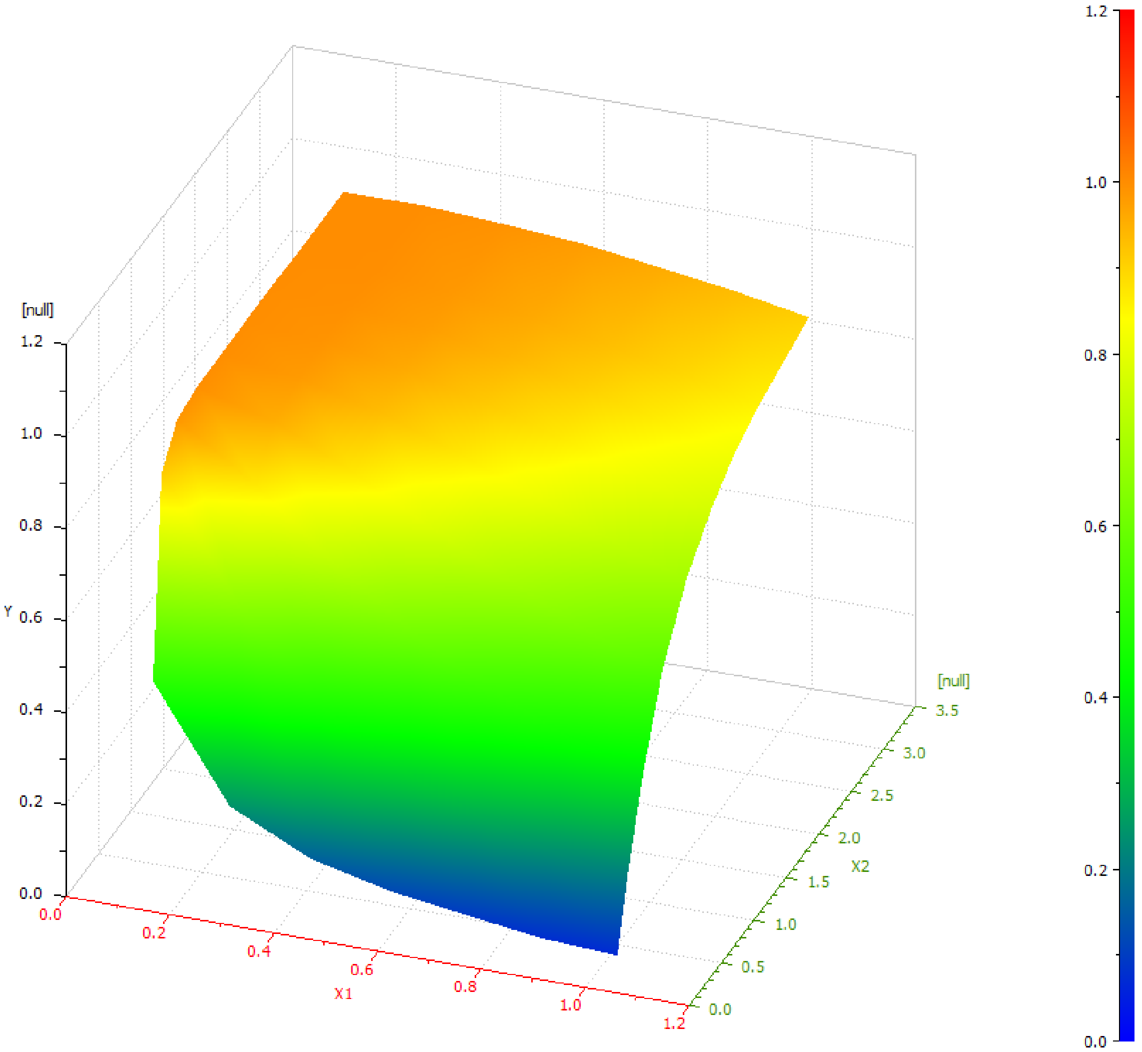

Figure 5.4. Heat exchangers effectiveness. Y is effectiveness, X1 hot mass flow and X2 cold mass flow.

As can be seen from Figure 5.4, effectiveness is highly dependent on the mass flow rates of the heat exchanger. Increase of cold flow increases cooling effectiveness and increase of hot flow decreases cooling effectiveness. Effectiveness ϵ is essentially the ratio between the actual heat transfer rate q and the maximum possible heat transfer rate q_{max}:

$$\epsilon = \frac{q}{q_{max}} \rightarrow q = \epsilon \cdot q_{max}. \tag{1}$$

Essentially, effectiveness is dimensionless quantity which ranges from 0 to 1 [21].

In order to calculate q_{max} we must consider the maximum possible heat transfer which may occur in counter flow heat exchanger of an infinite length. Basically, in this hypothetical situation either hot $T_{h.i}$ or cold inlet flow $T_{c.i}$ experiences maximum temperature difference $(T_{h.i} - T_{c.i})$. For example, in case hot fluid experiences greater temperature change $(|\Delta T_h| > |\Delta T_c|)$, hot fluid will be cooled to inlet temperature of the cold fluid

$(T_{h.o} = T_{c.i})$. Moreover, we consider heat capacity rates and use the smaller rate in calculations as follows:

$$C_c < C_h: \qquad q_{max} = C_c\,(T_{h.i} - T_{c.i})$$

$$C_h < C_c: \qquad q_{max} = C_h\,(T_{h.i} - T_{c.i})$$

From these equations we can make general expression:

$$q_{max} = C_{min}\,(T_{h.i} - T_{c.i}) \tag{2}$$

where C_{min} is equal to C_c or C_h, depending which is smaller. Equation provides maximum heat transfer rate that could be delivered in hypothetical heat exchanger of infinite length. [21]

Now if the ϵ, $T_{h.i}$ and $T_{c.i}$ are known, the actual heat transfer rate can be determined from the expressions and placed into the equation (1):

$$q = \epsilon C_{min}(T_{h.i} - T_{c.i}) \tag{3}$$

From any given heat exchanger can be stated that

$$\epsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right) \tag{4}$$

where C_{min}/C_{max} is same as C_h/C_c or C_c/C_h and NTU is dimensionless parameter defined as

$$NTU = \frac{UA}{C_{min}} \tag{5}$$

where U is the overall heat transfer coefficient and A is the heat transfer area. Further analogy between thermal and electrical circuits states that

$$UA = \frac{1}{R_{hot} + R_{wall} + R_{cold}}. \tag{6}$$

R_{hot}, R_{wall} and R_{cold} are the thermal resistance at hot fluid level, wall level and cold fluid level respectively. [21] All in all, when the thermal effectiveness and the thermal resistances are known, it is possible to calculate heat exchangers performances completely.

Heat exchanger could have been modelled also by measuring the dimension of the physical heat exchanger and then use analytical equations. However, this method would have been more inaccurate and susceptible for errors. Especially, Nusselt number and characteristics length are very hard to estimate and the parameters greatly influence to the results. Using effectiveness tables, results are more reliable.

Next usage of the Amesim’s heat exchanger model is discussed. Heat exchangers inputs and outputs are shown in Figure 5.5 and joining together in Figure 5.6. Heat exchangers are divided into two half exchangers which represent hot and cold side. Between half exchangers is heat flux calculation component which calculates the actual heat transfer between hot and cold fluids. Heat transfer effectiveness table (look Figure 5.4) is fed to heat flux model which uses it to calculate heat transfer amount.

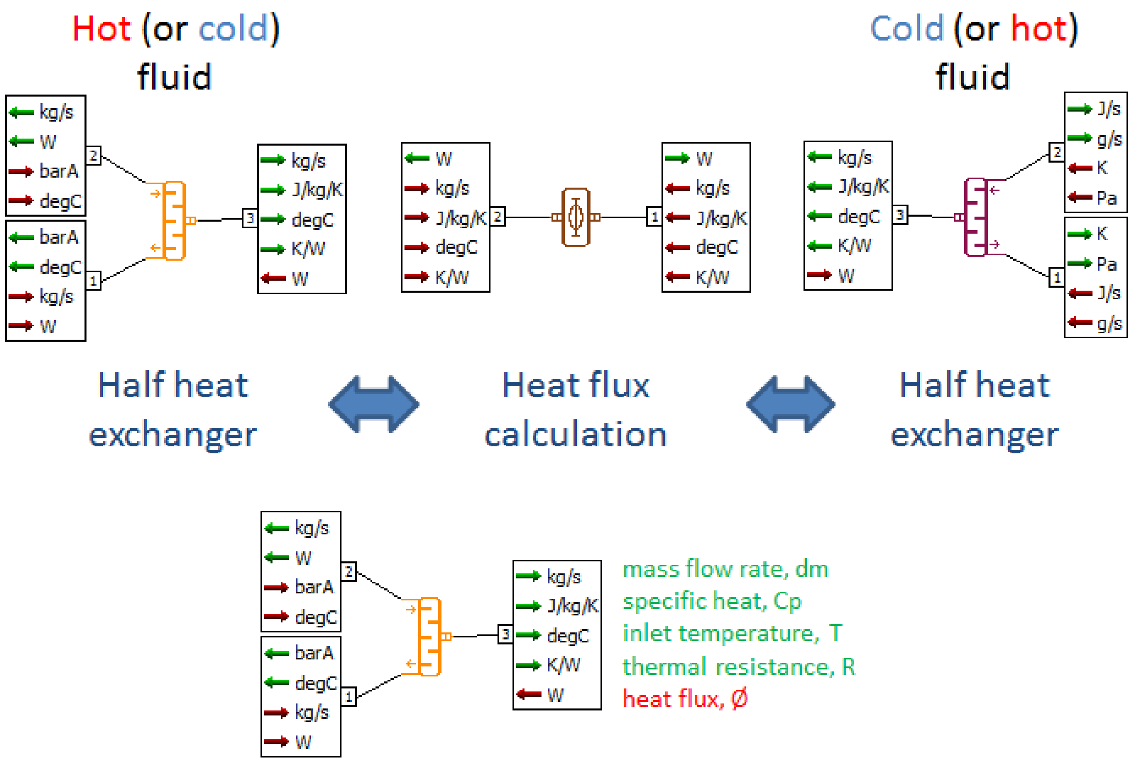

Figure 5.5. Heat exchanger inputs and outputs [40]

In this thesis only modeling of the primary heat exchange is discussed, hence it was the most challenging to model. Amesim’s half exchanger model contains only one inlet and outlet, whereas in reality heat exchanger contains two outlets (look Figure 3.5). In Amesim the heat exchanger model cannot be altered so that air would exit from two ports. This forces to make compromise in modeling. Most sensible way to model two passage-ways inside primary heat exchangers hot side is to divide hot side into two separate sections (look Figure 5.6). Basically, hot side is divided into cold corner and the warmer side (let us call it warm side). Warm and cold side have their own size and mass flow rates which represents reality very well. For instance, if flow rate to fuel pressurization increases also mass flow through cold side increases. Similarly, flow rates in warm side change depending on flow rates in air cycle air conditioning.

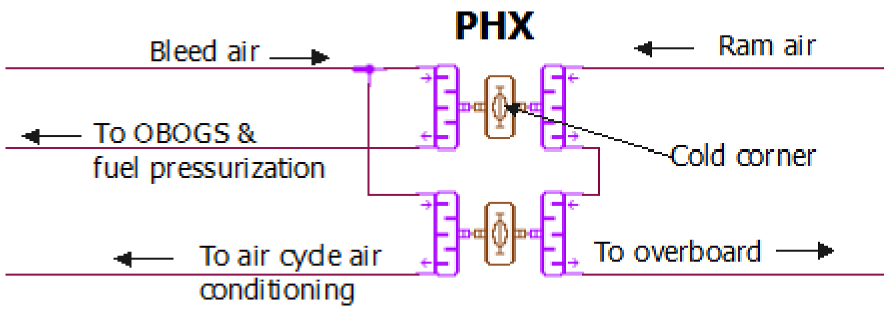

Figure 5.6. Block diagram of a primary heat exchanger

However, there is multiple things which are not taken into account. Firstly, after heat exchangers cooling element, flows are separated with simple fin that is not tight-knit and therefore allows colder and hotter flows to mix. This mixing is nonetheless not so considerable. Secondly, phenomenon is the mixing during flow through cooling element. Cooling fins are interconnected and do not form straight passageways. This allows air to flow slightly diagonally which in turn may affect to temperatures. Thirdly, cold air exiting from a cold corners cold side represents temperature average whereas in reality it is at very different temperature on the top part of the heat exchanger than in the lower parts. Basically, cold air warms up the most at the top part of heat exchanger and therefore lose some of its cooling potential. So, it is very hard to estimate does the cold air (average temperature) entering the warm sides cooling side have the same cooling effect.

When the model was tested we did not have enough measured data of the heat exchanger to indisputably state that model gives very accurate results. Nevertheless, it could be concluded that ram air most of the time warms up so little in the cold corners side that it does not affect greatly to the warm sides cooling effectiveness. However, model may become more inaccurate when mass flow through cold corner is at most. All in all, when the whole model is considered, heat exchangers are not the greatest source of inaccuracy.

5.5 Air cycle machine

The model of a ACM is shown in Figure 5.7. Compressor and turbine are on a common shaft. Shaft basically takes into consideration the friction of the air bearing and also transmits the torque between turbine and compressor. Turbine produces torque which rotates the whole assembly. Torque depends on the pressure ratio over turbine, current rotational speed and temperature. Similarly, compressors torque depends on the same values. ACM-model can be used for dynamic simulations, because characteristics of a compressor and turbine are taken into account.

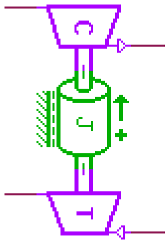

Figure 5.7. Block diagram of an Air cycle machine

Two tables have to be provided to Amesim in order to model compressors characteristics. These two tables are pressure ratio P_r and the isentropic efficiency η_{is} and both of them have to be provided the function of the corrected mass flow rate dm_c and the corrected rotary velocity ω_c. [41] These two tables are used for resolving the values of pressure ratio and efficiency. Typical characteristics curves of the pressure ratio and isentropic efficiency are shown in Figure 5.8 and Figure 5.9. Basically, values for P_r and η are resolved from 3 dimensional table and then used for further calculations. Be noted that these figures are examples, and illustrate imaginary characteristics curves. Real characteristics curves used are classified and cannot be shown.

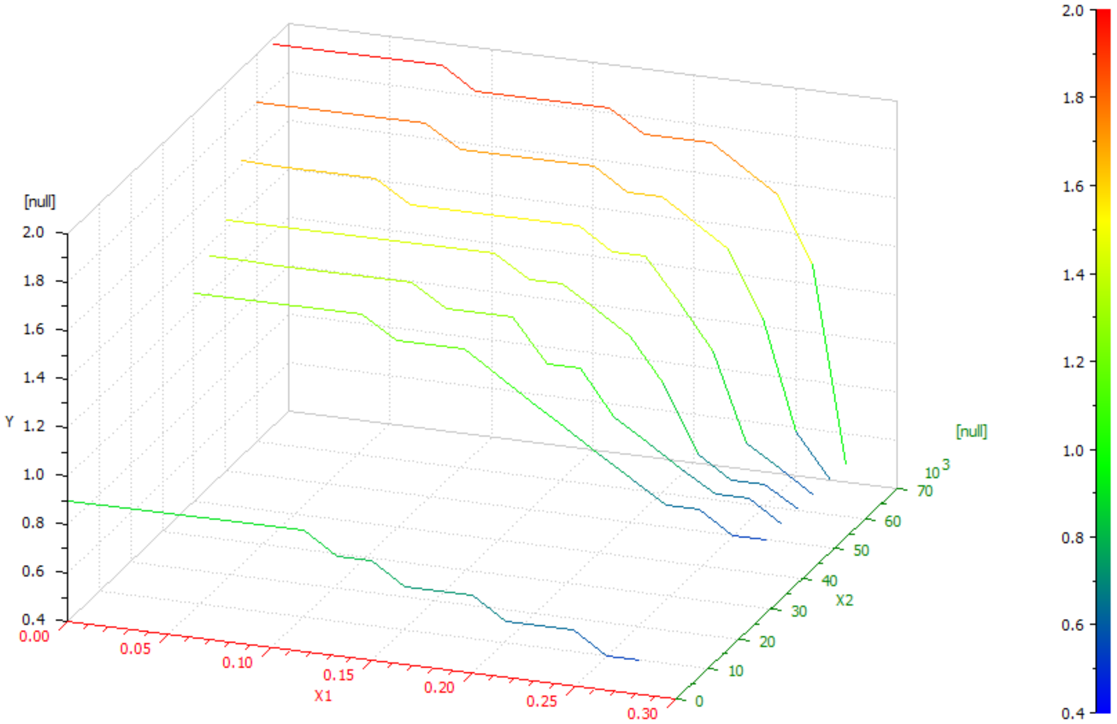

Figure 5.8. Compressor pressure ratio (Y) characteristics curve function of the corrected mass flow (X1) and corrected rotary velocity (X2)

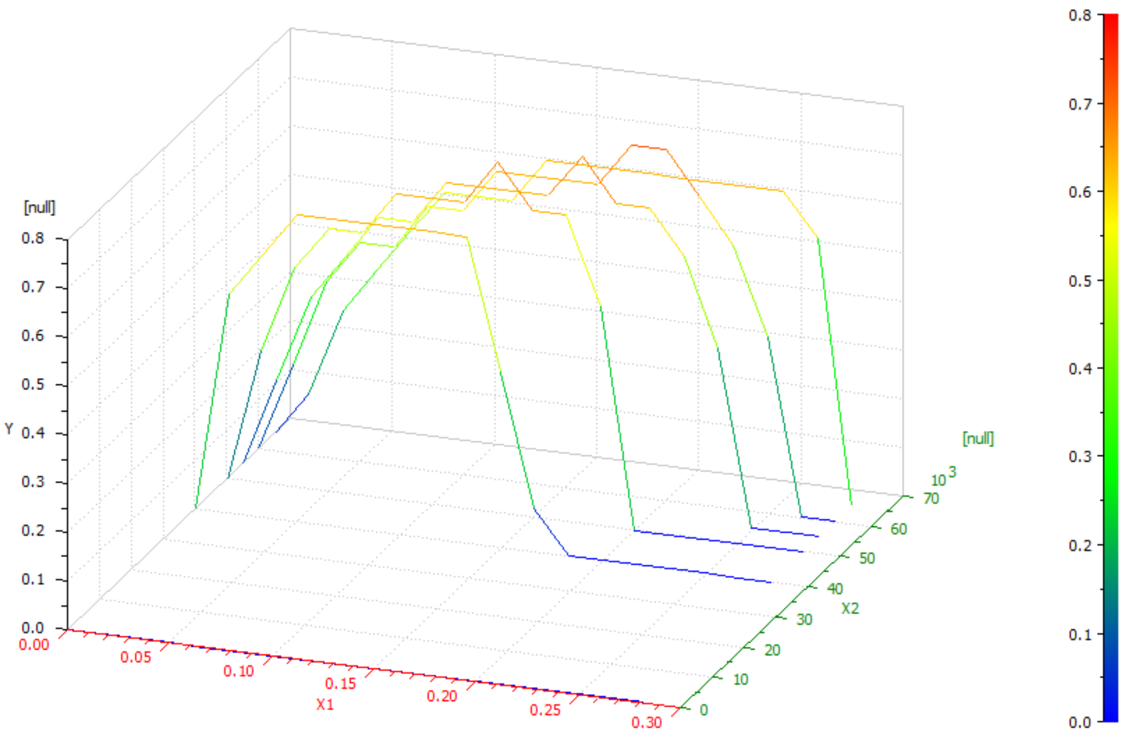

Figure 5.9. Compressor efficiency (Y) characteristics curve function of the corrected mass flow (X1) and corrected rotary velocity (X2)

Pressure ratios P_r characteristics curves needed were drawn from measurements conducted by aircraft manufacturer (Northrop Grumman Corporation). These measurements were made during aircrafts development and therefore can be considered very reliable. However, we cannot be completely confident on the results, since any description of the actual measurement method is not available.

Compressors efficiency η_{is} characteristics curves were calculated from the same measurements conducted by Northrop Grumman Corporation. But measurement results were given differing format. Change of the air temperature was given in function of a corrected airflow and compressor pressure ratio. Therefore, isentropic efficiency had to be calculated using the knowledge of the temperature change and pressure ratio. Needed equation was provided by SAE J1723:

$$\eta_{is} = \frac{T_{1SAE} \cdot P_{rSAE}{}^{0.286} - T_{1SAE}}{T_{2SAE} - T_{1SAE}} \tag{7}$$

where T_{1SAE} is the inlet and T_{2SAE} the outlet temperature $[°R]$ and P_{rSAE} is pressure ratio $[Psig]$.

Compressor-model is very accurate because of two characteristics curves. The model could be made more accurate only with sophisticated models from Amesim's CFD-library, but such model would increase simulation time very much. Also, compressor could be tested again in test bench in order to confirm old test results of Northrop Grumman Corporation.

Compressors external variables are shown in Figure 5.10 (green arrow output, red arrow input). These variables are used for calculations which give numeric values of temperature, pressure, torque, corrected mass flow rate and so on. Complete list of the variables is shown in Amesim user's guide.

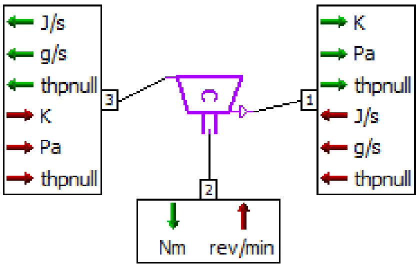

Figure 5.10. Compressors external variables

Compressors output and input values are computed using following expressions. Pressure ratio P_r is calculated with equation:

$$P_r = \frac{P_{down}}{P_{up}} \tag{8}$$

where P_{down} is downstream and P_{up} is upstream pressure. By default, the corrected mass flow dm_c is computed as:

$$dm_c = \sqrt{\frac{T_{up}}{T_{st}}} \cdot \frac{p_{st}}{p_{up}} dm \tag{9}$$

where T_{st} is absolute standard temperature and p_{st} absolute standard pressure. Corrected rotary speed is computed as:

$$\omega_c = \sqrt{\frac{T_{st}}{T_{up}}} \cdot \omega \tag{10}$$

where ω is rotary speed. The compressors outlet temperature T_{down} is resolved from the equation:

$$T_{down} = T_{up} + \frac{T_{up}}{\eta_{is}} \cdot \left({P_r}^{1-\gamma_s} - 1 \right) \tag{11}$$

where γ_s is isentropic calorific factor and defined with following relation:

$$\gamma_s = \frac{C_V}{C_p} \cdot \gamma_T \tag{12}$$

where γ_T is the isotherm caloric factor, C_V the specific heat at constant volume and C_p the specific heat at constant pressure. The isotherm calorific factor is further defined as:

$$\gamma_T = -\frac{P}{V} \cdot \left(\frac{\partial V}{\partial P} \right)_T \tag{13}$$

where V is the specific volume, P the pressure and T the temperature. If the mass flow rate is negative, then very low isentropic efficiency value ($\eta_{is} = 0.2$) is used to calculate outlet temperature. In practice, mass flow is never negative during simulation. Lastly, the compressor shaft torque is computed as follows:

$$\tau = \frac{dmh_{up} + dmh_{down}}{\omega} \tag{14}$$

where dmh_{up} is enthalpy flow rate at upstream and dmh_{down} at downstream. Basically, difference in enthalpy flow rate is divided by the rotary speed of the compressor.

Model of a turbine is very similar compared to compressor. The turbine-model also requires two similar tables which are pressure ratio P_r and the isentropic efficiency η_{is}. Both of them have to be provided function of the corrected mass flow rate dm_c and corrected rotary velocity ω_c. Unfortunately, there was neither knowledge of the pressure ratio nor the isentropic efficiency available, which made the modeling process very challenging.

Turbine model was developed as follows. First, characteristic curves were developed using only the typical values and educated guesses. Characteristics curves form could be estimated roughly by the size and the shape of the impeller. Also, knowledge about approximate rotary speeds of the ACM helped to estimate possible characteristics. Secondly, turbine was verified in one known working condition (0.7 Mach, hot day, at sea level) which is described thoroughly on next chapter. Basically, characteristics curves form was kept constant, but its location was changed so that ACM worked properly in one specific working condition. Lastly, turbine-model was tested in all possible situations. Characteristic curves were tuned so that neither maximum nor minimum rotatory speed were exceeded. Now the ACM does not exceed maximum normal rotatory speed because turbines efficiency decreases when mass flow exceeds nominal working conditions.

5.6 Cabin and avionics

The models of cabin and avionics are presented in Figure 5.11. As can be seen, cabin and avionic bay are interconnected like described in chapter 4. Basically all the key components and their functions are modelled. Only cabin ram air scoop and radar liquid cooling are left out. The model takes into account almost every physics phenomena which are relevant in the context of ECS.

Model takes into consideration the dynamic and static pressure. Basically, static pressure can be considered to represent very accurately ambient air pressure and the dynamic pressure represents pressure inside the ram air scoop. Thus pressure differences between ambient air and ECS air ducts can be modelled accurately. Further, mass flow amount is proportional to pressure difference over restrictions (hole, valve, choke point) and for that reason flowrate overboard can be modelled precisely.

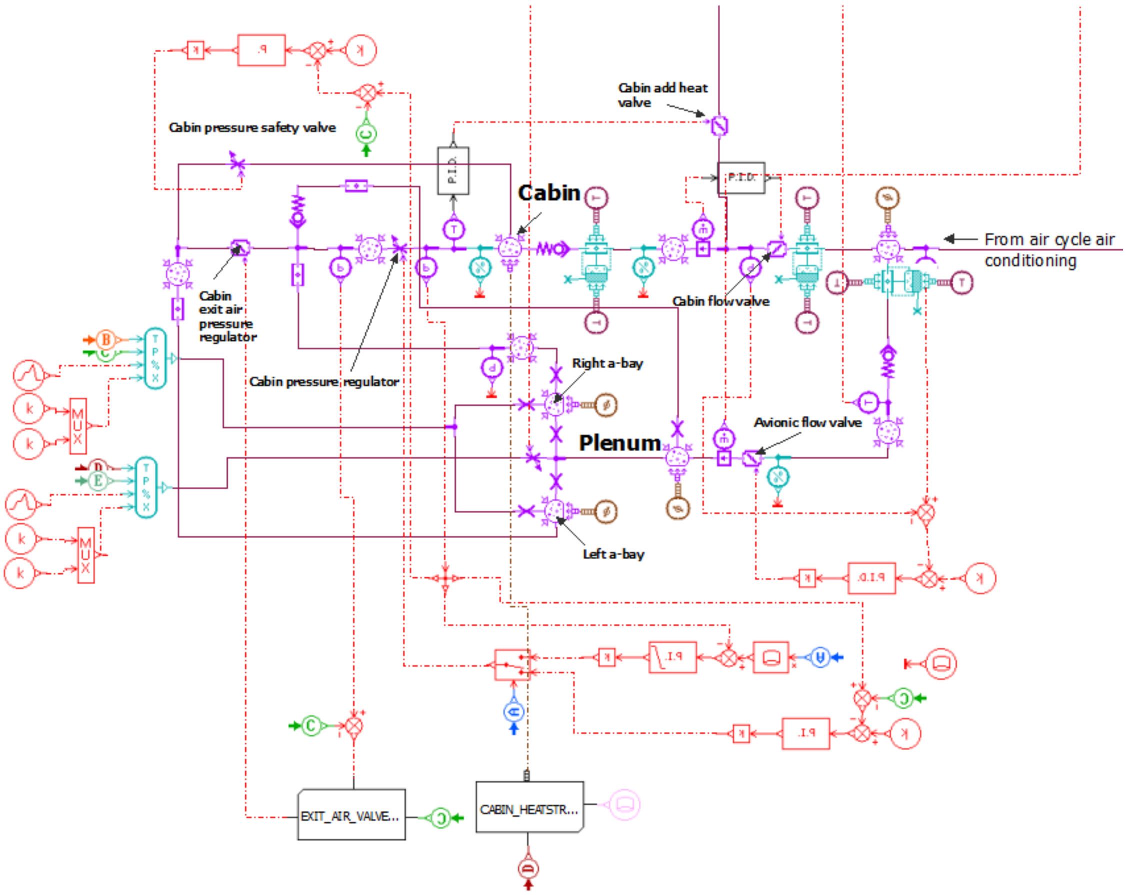

Figure 5.11. Block diagram of the cabin and avionic bays

Cabin is modelled as a large volume of air that could be imagined as a spherical tank. There is one passageway way in and two passageways out. Air exits through *cabin pressure regulator* and *cabin safety valve*. These valves are basically holes which cross-sectional area alter linearly proportion to the valves opening.

At first cabin was modelled as large isolated volume of air with no heat transfer. But during simulation testing it was discovered that heat transfer between canopy and ambient air could be as much as hundreds of watts. This large heat transfer has a significant effect on the temperatures inside the cabin. Although, temperatures inside the cabin do not affect to the dynamics of the ECS, it is still important to estimate temperatures. For example, without an accurate knowledge of the cabin temperatures, it cannot be tested how flow schedule modifications affect to the pilots flying comfort.

Cabin model simulates all the necessary situations imaginable. First, ambient temperature affects to temperature inside cabin. Second, *cabin safety valve* and *cabin pressure regulator* permit flow for both directions. For instance, if ambient pressure rises beyond cabin pressure, safety valve evens out the pressure difference by allowing air to flow to the cabin. Third, cross-sectional area changes linearly which represents real valves behaviour accurately. Last, all the air duct has been modelled. So, mass flow amount in all the ducts represents reality very accurately.

Model of the avionic plenum is similar to cabin model. Basically, the plenum can be imagined as volume of air to which multiple air ducts are connected. Air can enter the plenum from the avionic ram air duct, *avionic flow valve* and from space after cabin pressure regulator. When air exits plenum, it can only flow to left or right avionic bay. Both of the avionic bays are simply modelled as a single volume from which air can flow over board almost without resistance.

In reality, plenum is a rambling bladder from which air flows to all avionic equipment. Equipments are packed in over ten casings and every casing has its own passageway from plenum. Further, these casings are situated either left- or right avionic bay. Even further, left- and right avionic bay are both divided into three separate spaces which are interconnected. Lastly, from left and right avionic bay, air flows overboard from single rectangular hole or leak out from the small gaps in fuselage.

Accurate model of the whole avionic bay would be unnecessary complex and almost impossible to accomplish. Now the model is simplified to great extent and it contains only one passageway to each of the avionic bays and airflow goes through one single choke point. Choke point restricts airflow and causes small pressure rise in plenum. Plenums pressure corresponds reality perfectly when mass flow and ambient pressure are at specific value, but even minor changes to plenums input values cause inaccuracy of the plenum-model. Consequently, plenum-model was detected to cause too high pressures at high altitudes, when pressures match perfectly at sea level. Essentially, plenum-model is now too simplistic for specific situations and needs to be modified in the future.

Plenum-model can be improved by adding more passageways or using very high flow coefficient. Basically, the problem is too high pressure at high altitudes. In other words, when pressure between ambient and plenum is highest, air do not flow as freely as needed.

Situation can be improved by lowering flow resistance by adding more passageways and increasing flow coefficients value.

Advanced pipe-models are used all the way to the cabin and avionics. Advanced models are needed so that airflow can be modelled precisely. Without an accurate model of the airflows inertia, airflow would in some situations change its direction or velocity very rapidly. It was discovered that without inertia-model the fluid changed its direction instantaneously and caused very chaotic results. For example, air flowed even opposite direction of the *cabin flow valve* and therefore caused temperature to rise in avionic bay. But when inertia was added to pipe-models, changes in same situations were more sedate.

Advanced pipe-models are also needed to model humidity. At this point, we are not directly interested in humidity, but it may give some extra information of the ECS. For instance, high level of relative humidity may suggest that occasionally icing is a real threat.

All the valves and their functions have been modelled. Valves get either temperature or pneumatic signal and react to it accordingly. Valves are interacting and react to each others movements.

5.7 Control System

The model of a control system basically consists of sensors, PID-controllers and logical operators. Sensors measure the temperature or pressure and send value to the PID-controllers. The PID-controller compares received signal to the reference input and acts accordingly. PID-controllers have either fixed or variable reference input. In order to model all of the real-life functionalities few logical circuits are also added.

In the Figure 5.12 is shown the control logic of the *system flow modulating pressure regulator*. Particular valve illustrates well how the valves are controlled and how the special functions can be implemented. Valve in question only modulates the mass flow amount. Basically, measured mass flow signal comes from port 1 and it is compared to the reference input. Reference input changes in relation to the avionic flow temperature. Next error signal is calculated in summing junction and depending its value PI-controller command valve towards open or close position. After PI-controller second-order-lag emulates characteristics of the valves movements. Second circuitry which inputs are from port 2 and 3, models the over temperature function. Basically, if measured temperature from compressor or turbine exceeds predetermined limit, then *system flow modulating pressure regulator valve* is commanded towards close position. If temperatures are at acceptable level, then second circuitry does nothing.

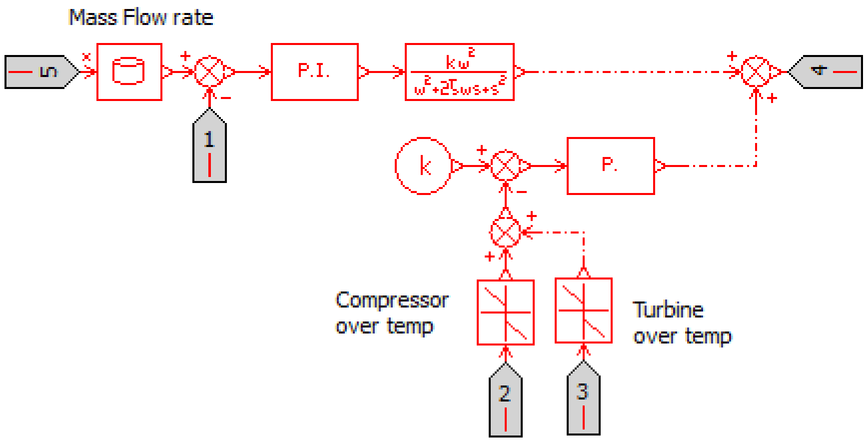

Figure 5.12. Control logic of a system flow modulating pressure regulator valve

Figure 5.13 shows logical operations which can be used for more complicated controlling functions. This particular circuitry models operation of the ram air servo which controls the *avionic ram air valve*. Ram air servo opens *avionic ram air valve*, if the pressure difference over the *system flow modulating pressure regulator valve* is too low and simultaneously upstream pressure of the same valve is also too low. And further, if downstream pressure is under the predetermined limit ram air servo commands *avionic ram air valve* to open. From port 2 system receives downstream pressure and from port 3 upstream pressure of the valve. Constant-blocks are the predetermined pressure limits to which down- and upstream pressures are compared to.

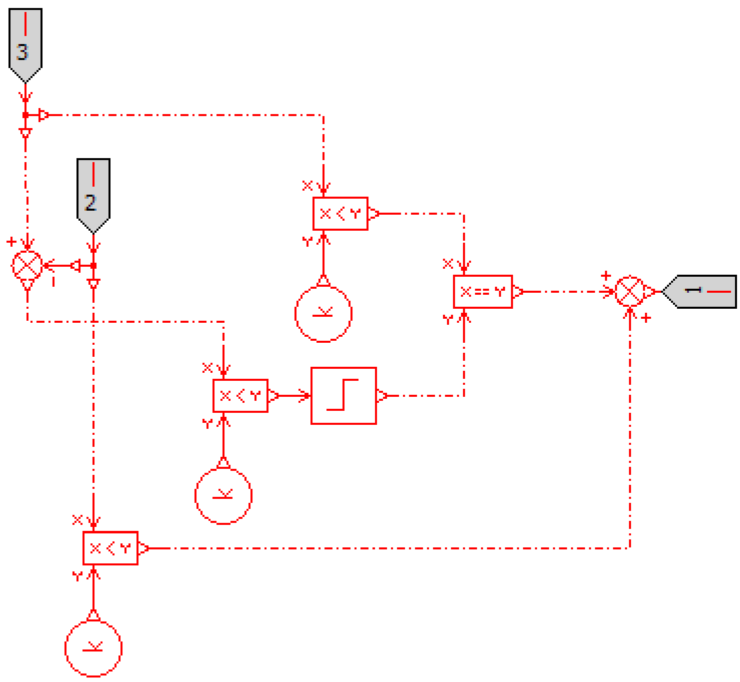

Figure 5.13. Logical operations of a ram air servo

The primary target of the control-system-model is to mimic valves dynamic behaviour as accurately as possible. Therefore, we are not interested what exactly happens in reality, instead the systems response to different situations is our only interest. Objective is to accurately model every valves response to changing temperature or pressure. When separate valves and their responses are modelled, whole models dynamic responses can be examined. Basically, every valve and its controller are simplified mathematical representations of the reality. Model does not consider mechanical structure of the valves, but resembles the mechanical behaviour.

Some of the valves are actuated with PID-controller even though in reality these valves are fully pneumatic and do not receive electronic signals from a control system. For instance, *cabin safety-*, *cabin pressure regulator* and *avionic flow valves* movements are modelled by using PID-controllers. Basically it does not matter how the valves actuation is modelled, if it represents real behaviour relatively accurately. For example, in reality *avionic flow valve* gets pneumatic signals which forces valve to move. In this model *avionic flow valve* gets imaginary pressure signals which controller interprets and then forces the valve to move. Results resemble each other if controller gains are chosen well.

5.8 Simplification of the simulation model

Models need to be simplified for countless reasons. First of all, every added detail to the model also adds possible source of error. Also, when multiple complex submodels are stacked on top of each other, every single one of the submodels may also increase errors of other submodels. Secondly, simulation time increases when complexity is added. Simulation time may increase even exponentially if multiple variables are tied together and influence each other. Thirdly, creation of detailed model is time consuming. Details add time consumption of every aspect of the modeling process: errors are harder to discover and resolve, verification and validation are harder to implement, testing of the model is more time consuming and actual model construction takes more time. Altogether, model and its purpose has to be understood profoundly so that a more simplified model can be created in a way that ensures accurate results.

Some models can be easily implemented without the concern of adding source of error. For instance, when more complex models of the pipes were implemented for this thesis, we could be certain that uncertainties would not increase. We did not have to give more parameters and the number of output values stayed the same. The only change in practice was that calculations became heavier and therefore simulation time increased. Also, because pipes basically only affected to the pressure losses, we could be certain that it did not increase errors of other models.

Yet another reason for a simplified model can be the lack of knowledge. For instance, in order to model mechanism of the pneumatic valve, one would have to possess the knowledge of multiple springs constants, friction between parts, size of orifices, diameters of passageways and area of diaphragms. Every single one of these parameters have to be measured or estimated and since analytical estimation increases uncertainties, model would be unreliable. For these reasons, complicated mechanical structures have been left out, because modeling them would only increase uncertainty.

Ejectors and their operation have not been modelled. Basically, ejectors are inefficient air pumps that accelerate flow inside ram air ducts. Ejectors could be modelled, but it would require much more complex model. At this stage, we do not require such model, but in the future, ejectors might be needed. Especially, the increase of ram air during ejectors operation have a significant effect to heat exchangers outlet temperature.

Fuel pressurization is taken into account, but the model is kept as simple as possible. Fuel pressurization requirement changes proportion of the fuel consumption and fuel consumption follows the engines throttle position. Also, flight speed, altitude and engine rev affect to fuel consumption, but affect is almost negligible. Therefore, the most sensible way is to use throttle position for estimation of a mass flow.

Radar liquid cooling normally utilizes only ram air. In exceptional situations, ram air scoop closes and air from avionic plenum is used instead. This rarely happens and therefore modeling this function would be unnecessary.

Anti-ice and rain removal functions are not modelled. These functions have a significant effect to temperatures inside ducts after primary heat exchanger. But while these functions are not operational they do not have any effect to temperatures. Anti-ice and rain removal will be modelled if these functions are needed in simulation.

At this point, water separator draining and water spray function is not modelled. Drained water could be taken into account by increasing absolute humidity in secondary heat exchangers ram air duct. At high altitudes drained water amount is negligible, but in very humid climate heat exchangers efficiency increases markedly.

Heat transfer between pipes outer layer and surrounding air is not modelled accurately. There is not precise knowledge of the temperatures inside fuselage during the flight and therefore temperatures cannot be added to the model. This nonetheless has a negligible effect to the temperatures inside ECS.

6. MODEL VERIFICATION AND VALIDITY

This chapter discuss verification and models validity. Verifications were done using all the available data. Simulations were compared to many different measurements which were gathered using different measurement methods. Process itself was iterative, since all the verification results affect to each other. Verification of the air cycle air conditioning and the entire ECS in static situation needed to be done multiple times so that results were satisfactory in both of them simultaneously. Only final and the best results are shown in this chapter. Verification results are also used to assessment of the simulation models validity.

6.1 Ram air scoop verification

Ram air verification was done by comparing the simulation results to the measured values. Measured values are from Northrop Grumman Corporation's rigorous testing which took place during aircrafts development process. Main interest is the mass flow rate in both ram air ducts at different aircraft velocities. Results are shown in Figure 6.1.

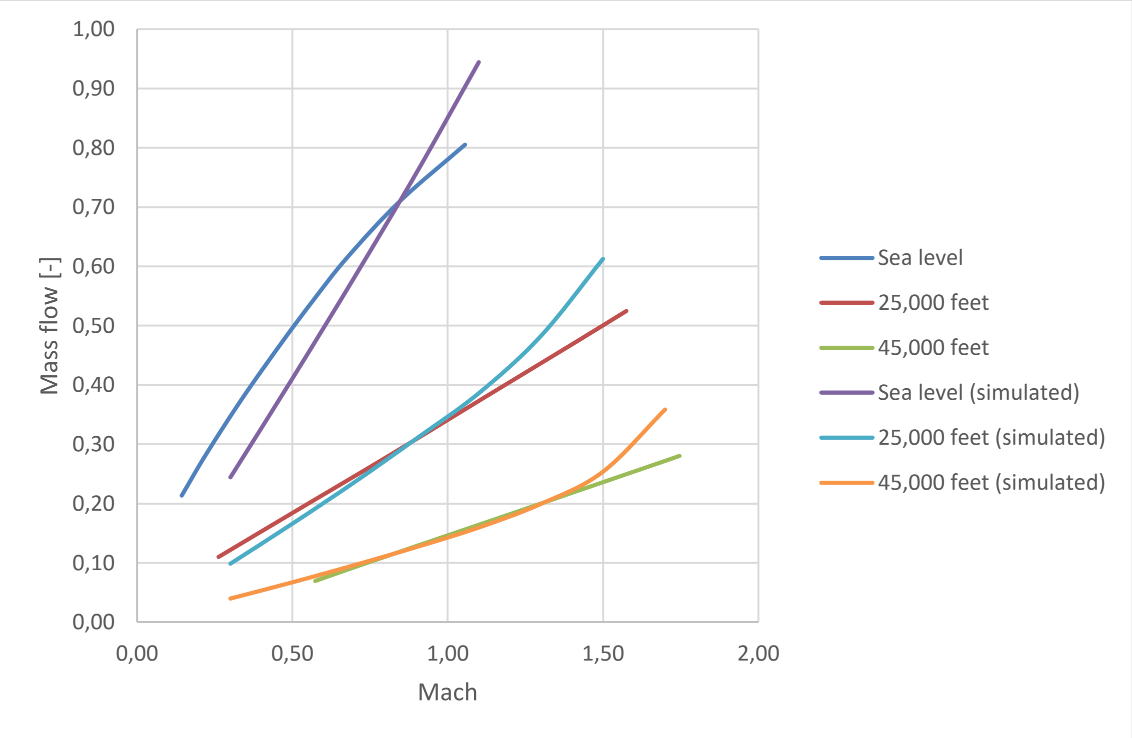

Figure 6.1. Mass flow rate in ram air ducts at different aircraft velocities

As can be seen from the results, the simulation model follows real values well at high altitudes. However, when velocity increases the simulation model starts to give too high values compared to measured ones. At certain points mass flow starts to increase sharply in parabolic curve whereas in reality all the characteristic curves are relatively straight. Higher the altitude the later the simulation results start to differ from reality.

Simulation model is most inaccurate at sea level, basically when air is densest. In reality mass flow curve rises fast when velocity increases, but the growth of the mass flow eventually slows down. Basically, mass flow increases so much that flow through the heat exchangers starts to saturate. Increase of mass flow increases the pressure loss through heat exchangers and eventually pressure loss becomes so great that flow is saturated. Simulation model does the opposite and its characteristic curve rises parabolically. Because model only considers pressure difference over heat exchanger and does not take into account growing friction or choking, mass flow continues to rise. Further, pressure difference over heat exchanger is the greatest when air is densest and for that reason the difference between reality and simulation is also the greatest.

The model can be considered usable, despite great differences in mass flow rate between simulation and reality at low altitudes. Basically, mass flow rate at low altitudes are so great, that heat exchangers have very high efficiency. Meaning moderate increase or decrease of mass flow do not have considerable effect on temperatures or heat transfer rate. Accuracy of mass flow rate becomes more important when ram air amount decreases which in practice means higher altitudes. The higher the altitude the better the models accuracy. The simulation model is now most accurate at higher altitudes.

The model covers well all the common flight situations, but at the same time, all the extreme situations cannot be simulated accurately. For example, when aircrafts velocity is low, ejectors effect greatly to ram air amount, which is not taken into account. Also, at low altitudes and especially at low velocity ram-air-model happens to be inaccurate even when ejectors are not considered. Still another problematic situation are the top speeds. Top speeds change greatly function of an altitude. The higher the altitude the faster the safe velocity. Now model gives much higher mass flow rates at all altitudes that it would be in reality. This has a significant effect to models accuracy especially at highest flight altitude, since ambient air is cold and therefore can cool bleed air effectively. But simultaneously ram air flow is relatively low which basically means low efficiency of the heat exchanger. Now if the ram air amount at high altitudes is much higher than in reality, heat exchangers efficiency is much higher, which further causes inaccurate temperatures inside the ECS.

Altogether, model of a ram air can be considered accurate enough in most situations. Model does not behave like real system, which causes inaccurate results in extreme situations such as at top speeds or slow flying. Basically, the nearer the velocities are extreme values the greater the inaccuracy. Moreover, models accuracy increases when altitude increases. It can be stated that model is the most accurate between 25,000 and 45,000 feet altitude when velocity is ranging from 0.5 to 1.25 Mach. Outside of this region, simulations can be done, but when results are inspected extra caution is advised.

6.2 Verification of the air cycle air conditioning

Model of an air cycle air conditioning was verified with documents provided by aircraft manufacturer Northrop Grumman Corporation. Document gives the knowledge of the temperatures, humidity and the pressures in one specific flight situation. In this situation aircraft is flying at 0.7 Mach at sea level on a hot day (40 °C). Simulation results were simply compared to the documents values.

Actual verification process was iterative and all the parameters were tuned using trial and error method. Basically, at start we only had an accurate model of a compressor and it worked as a fixed starting point. If temperatures and pressures were correct before and after compressor, we could deduce that also mass flow and rotational speed are correct. It is possible to match temperatures and pressures only in one specific working point of a compressor. To get the compressor to work properly, also turbine had to be matched so that it transmitted the right amount of torque to the compressor. At this point all the pressures and temperatures were relatively close to reality. After many more iterations, such parameters were found that all the temperatures and pressures were very close to reality and therefore all the components had to give accurate results.

Final results are very close to the values of the Northrop Grumman's document. However, it turned out to be impossible to match values perfectly. For example, either temperature or pressure could be matched after compressor, but not both simultaneously. Now the parameters are chosen so that temperature and pressure are both near the documents value. Actually parameters were chosen to match both temperatures and pressures as accurately as possible throughout the air cycle air conditioning .

Verification process described above gives a very good estimate for heat exchangers and their performance. The pressure changes affects to heat exchangers efficiency very little, so verification in one known working condition gives a very good estimate for all situations. The only exception is the secondary heat exchanger which contains water spraying assembly. Secondary heat exchangers efficiency may change noticeably when absolute humidity levels are high.

Turbine verification is speculative with this method. Hence compressors pressure and the temperature could not be match perfectly, errors accumulate all the way to the turbine. Now turbine is tuned to spin compressor at desired speed and simultaneously to cool down the air to the right temperature. Exiting air from turbine is at right temperature, but these results can be achieved with multiple parameter combinations. The difference between these combinations are small but not negligible. So basically with this method we cannot be certain of the turbine models accuracy, but it still gives a very good estimate.

ACM should be verified in at least two different working conditions. Ideally these conditions would be two different extremes, for example very low and very high mass flow conditions. If model matches both of them, then can be assumed that it gives an accurate result in all situations between. Now verification leaves room for doubt.

To conclude, verification gives a very good results for heat exchangers, but ACM results are unreliable. Very accurate model for heat exchanger can be created if one working condition is known. In contrast, ACM efficiencies, temperatures and pressures change considerably and knowledge of the multiple working conditions have to be acquired in order to get an accurate model.

6.3 Verification of the entire ECS in static situation

The pressures in all test ports were measured during the aircraft ground testing and compared to simulated values. The results are shown in Figure 6.2 and test ports (TP) locations in appendix B. Pressure results are scaled from 0 to 1 and bars are in right relation to each other.

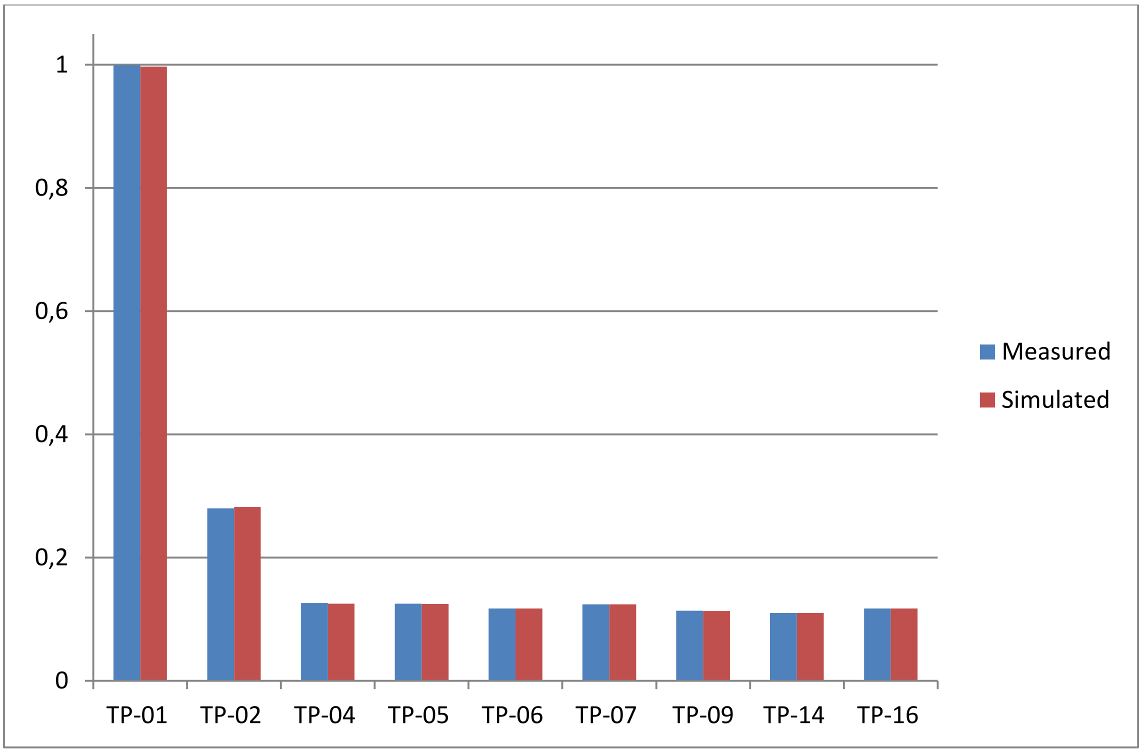

Figure 6.2. Measured and simulated pressures in static situation

Measured values were obtained with special device designed specifically to the task. During ground testing the device measures pressures from all the ECS test ports simultaneously and constantly refreshed the measured values. The aircraft itself was attached to the ground so that throttle could be used same way as during a flight. In Figure 6.2 situation, throttle position was set to value which results specific pressure in jet engines bleed ports. After desired pressure levels were obtained, throttle was kept at constant position and pressures were measured.

During ground operation ECS stabilized very fast after throttle position was set to desired value and the pressures stayed almost constant. In fact, pressure fluctuations were so small that sensors barely detected pressure changes. Values were shown in real time on the computer screen and pressure values could had been collected even with human eye. Since, pressures were very easily measured and did not fluctuate, these values are ideal for the verification of the simulation model.

As can be seen from Figure 6.2 simulation results are virtually perfect in one specific situation. From these results can be concluded that simulation model is constructed well since pressure changes in right proportion throughout the ECS. Basically, valves, pipes, compressor, turbine, heat exchangers and restrictions cause pressure losses that are representative compared to reality. Also, the simulation models control system regulates the pressures to the desired values. As a matter of fact, all the pressures after TP-04 were matched easily by fine tuning the parameters and the results were ideal. Only test port which could not be matched perfectly along with the other test ports was the TP-02. This must be due to compressor- and turbine-models which are not ideal and therefore pressures do not match precisely in this particular situation. However, TP-02 result is close enough, since the difference is as large as the differences between aircrafts. During this measurement task, measured values were also compared to over 40 other similar aircrafts results. Be noted, that simulation model still tries to resemble one particular aircraft and not the average of them all.

Despite the fact, that simulated pressure values match almost ideally in typical ECS working condition on a ground level, the results give no guarantee of the simulation models accuracy at high altitude situations. First of all, pressure differences between ambient changes considerably at high altitudes and all the valves have therefore completely different opening. Situation as a whole can be considered considerably different. Illustration of this, is the avionic pressure which was mentioned earlier to be too large at high altitudes, if the simulation model results right values near the ground level. In addition to this, also temperatures change considerably which changes the heat transfer rate via heat exchangers and canopy. As a result, valves which regulate temperatures are totally different position and thus effect to pressure. Even further, controls system also works differently at high altitudes and adds its own uncertainty to the simulation. In short, at high altitudes ECS working characteristic changes significantly and verification using ground testing results give no guarantee of the simulations model accuracy.

In order to get good results simultaneously to the low and high altitude simulations, simulation model has to be modelled so that it takes into account all the physics phenomena. Ideal results can be achieved in one specific condition even when some of the submodels do not represent reality very well. For instance, when mass flow amount changes some of the restrictions may start to give wrong values and cause too high or low pressure losses.

This brings up the problem mentioned multiple times before, we must possess knowledge of the multiple working conditions in order to undoubtedly verify the submodels and their modeling methods. Now we do not have measured values of the pressures during an actual flight, because such a measurement method or device does not exist. We however have a way of roughly estimate the working conditions of the ECS by measuring the pressure inside the cabin, as discussed in next section.

Despite the short comings mentioned, these results shown in Figure 6.2 suggest that model is constructed relatively well and that accurate results are possible to achieve if all the phenomena can be modelled in the right way. Major problem of achieving this ideal simulation model comes from the complexity of the entire system and its many interacting elements. It can be concluded with high possibility, that if one could possess knowledge of the pressures during high altitude flight, simulation model could be tuned to very high precision. Results would not most certainly be as good as in Figure 6.2 in all working conditions, but very near it.

6.4 Verification and validation of the entire ECS in dynamic situation

Dynamic response of the simulation model cannot be verified without measured data from the test flight. However, data stored into flight recorder is very limited and contains only information of the system errors. We do not know the valve positions, temperatures or mass flow rates. Because system itself is a black box and cannot be monitored directly, we were forced to measure conditions in the cabin. Basically, pressure and temperature were measured with *MSR 145* data logger during a specific flight situation. ECS was tested in situation which is the most unstable and thus also the dynamic response is most prominent. Simulated and measured pressure values are compared in Figure 6.3. Be noted that first 20 seconds is for testing settling time of the simulation and the real simulation starts at 20 second mark. Also, at 80 second mark, aircraft starts fast descent.

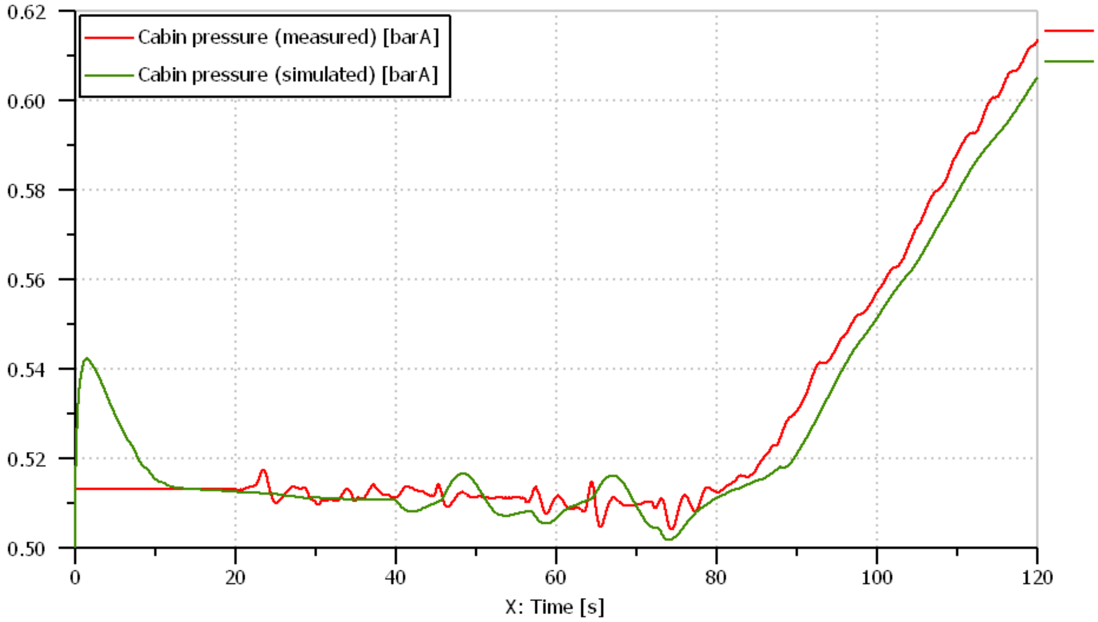

Figure 6.3. Difference between measured and simulated cabin pressure values in dynamic situation

In Figure 6.3 system was deliberately but to most unstable situation so that dynamic response and stability can be inspected. Aircraft was flying at 45,000 feet and velocity ranging between 230 to 265 m/s (0.68 to 0.78 Mach). Basically, throttle position was altered rapidly so that bleed airs pressure changed as much as possible. Pressure was the whole time under the *primary bleed air pressure regulator and shutoff valves* predetermined target pressure and thus these valves were fully open. In this particular test, throttle position is altered from high-throttle to low-throttle position twice which resulted bleed air pressure change shown in Figure 6.4.

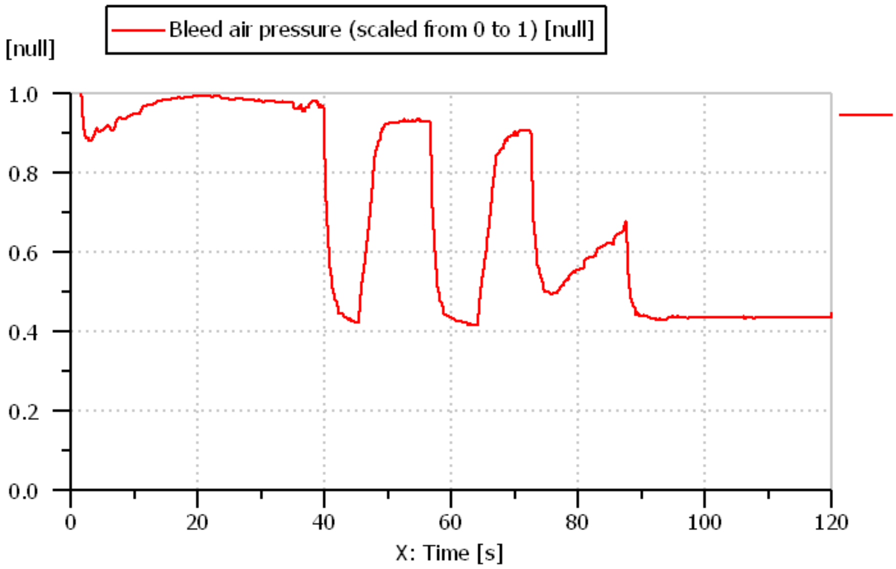

Figure 6.4. Bleed air pressure

As shown in Figure 6.4 bleed air pressure drops and rises sharply. Sharp pressure changes affect to valves desired position. When pressure decreases ECS valves must react to this by moving towards open position and when pressure increases valves must do the opposite. The greater the bleed air pressure fluctuation, the greater the valves movement must be in order to compensate pressure changes. This maximum bleed air pressure fluctuation can occur only at very high altitudes when jet engines do not produce high bleed air pressures and therefore pressure stays under *primary bleed air pressure regulation and shutoff valves* target pressure.

As can be seen from the results, simulation model does not represent dynamic response very closely. Pressure fluctuations amplitude is representative but the response time differs greatly. Real system is at least twice as fast as the simulated one. Also, the real system can be considered more restless, because simulation model only reacts to major pressure changes. When aircraft starts to descent, simulation models pressure rise lags behind.

Despite the slow reaction of the simulation model, it seems that it reacts as the real aircraft but much slower. During testing of a multiple situation, simulation model was always too slow, but the curves drawn from the pressures resembled real-life situation. In other words, the forms of the curves were partially similar. This suggests that valves react to the response as in reality, meaning the order in which valves start their movement may be correct. This further means, that simulation model gives a hint of how the real ECS reacts to the response. But it has to be noted, that results at this point cannot be considered more than a guidance, as illustrated next.

Pressures were measured from two different aircrafts, which did exactly the same procedures. Simulation model is constructed using ground testing results only of the other aircraft. Results in Figure 6.3 are from the aircraft that represented less the simulation model.

As can be seen, simulation model does not represent measured values at all and the curves have no similarities. This might be a result of multiple reasons, but one possibility is that aircrafts are significantly different from each other. If that is the case, simulation model can accurately represent only one of the aircrafts at the time. And when we consider the difficulty of modeling accurately even one complete ECS system, it may be impossible to achieve model that represents dynamic response. This particular aircrafts ECS system may just be too chaotic to be modelled precisely. More research of the dynamic response is needed so that limits of the simulation models capabilities can be found.

At this point model seems to be valid for some simulation investigations. Dynamic response and stability cannot be studied reliably. However, after ECS stabilizes, all the temperatures, valve positions and possibly pressures can be explored. Using simulation, knowledge of the conditions inside ECS can be acquired and it may give valuable information. But it has to be kept in mind that in reality ECS may not find complete stability and simulation model can be utilized reliably only for typical flight conditions. Another possible way of utilizing the simulation model, is to test how modifications effect to the system. For example, it is possible to test how old and inefficient heat exchangers affect to the system. In conclusion, though simulation model seems usable, further and thorough testing is still required.

7. SIMULATION STUDIES

In this chapter, two different examples of the simulation model's usage are presented. First, the effects of the cabin flow schedule modifications are briefly viewed. Second, valve co-operation is studied in order to gain greater knowledge of the system dynamic behaviour. Finally, future experiments are discussed. This chapter gives an understanding of the simulation model's potential and shortcomings.

7.1 Effect of cabin flow schedule modification

During ground service, the cabin flow schedule can easily be modified. Modification is useful if the objective is to maximize power output of the jet engines. When cabin flow rate is decreased the bleed air amount also decreases.

Next the effects of cabin flow modifications are studied. Flow schedules from 90 % to 110 % of the default setting are compared. Examples are from the same situation as the section 6.4 example (45,000 feet, rapid throttle alternation). Pressures in the bleed air ports are shown in Figure 6.4. Flow schedules' effects to heat exchanger outlet temperatures to the air cycle air conditioning are shown in Figure 7.1.

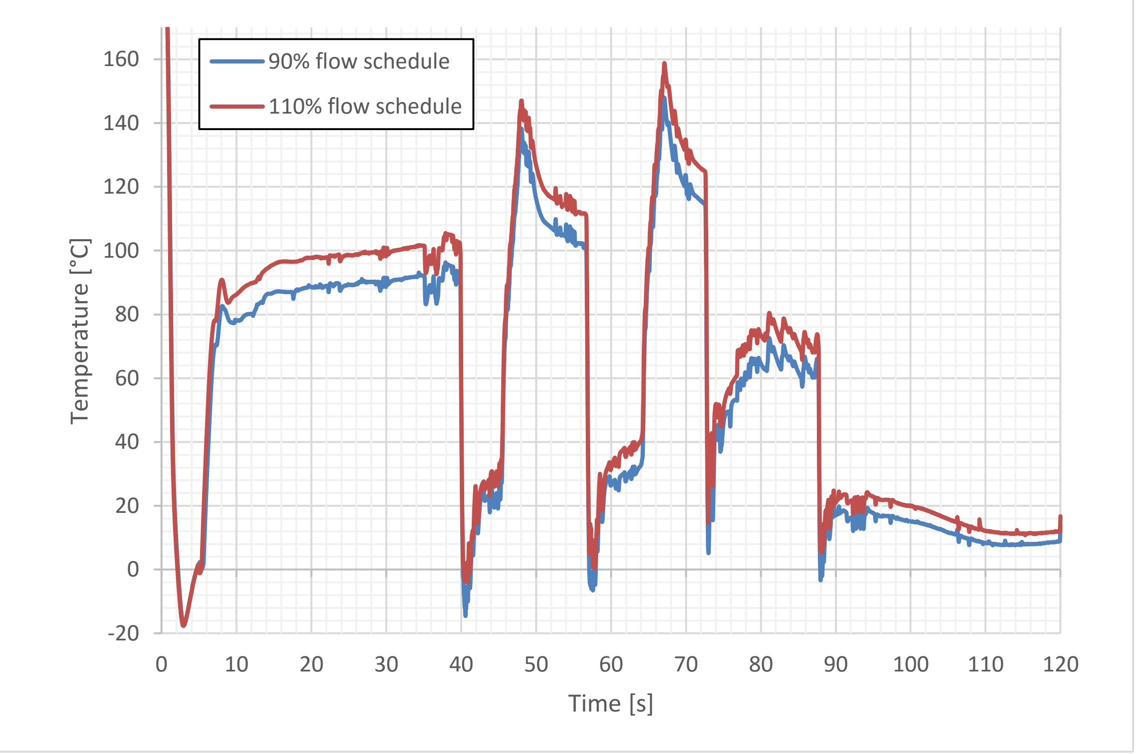

Figure 7.1. Primary heat exchangers outlet temperature to the air cycle air conditioning with 90 % and 110 % cabin flow schedules

As the Figure 7.1 illustrates, increase of cabin flow leads to greater temperatures inside ECS. Air temperature changes roughly up to 10 degrees centigrade. This temperature rise is mainly caused by the increase of mass flow through the heat exchanger.

Moreover, from Figure 7.1 it can be seen how drastically temperatures are affected by mass flow rate. When ECS supply pressure drops rapidly (40 second mark), mass flow rate also drops until valves react to the change. Movement of the most crucial valves is shown in Figure 7.3. First, when pressure plummets the mass flow also decreases very fast. As a result, for a short time period only a very small amount of air goes through the heat exchanger’s hot side which in turn causes low temperatures. Temperatures then start to rise as the *system flow modulating pressure regulator* moves towards an open position, but temperatures do not rise significantly until the *avionic flow valve* also moves towards open. When both of these valves are largely open, air flows in great extent to the avionic bays. Increase in mass flow ultimately causes a spike to the temperature curve (48 second mark). The simulation model suggests that temperatures can reach up to 160 degrees centigrade. Lastly, temperatures decrease gradually to the normal level when the system stabilizes. At this point it has to kept in mind that the simulation model’s dynamic response does not represent absolute reality, but nevertheless simulations give more knowledge of the system’s temperatures.

In Figure 7.2 the *cabin add heat valve’s* position is shown in the same situation. The figure illustrates how much valve position must change with different cabin flow schedules in order to keep cabin conditions constant. Hence with high mass flow rates temperatures inside the air cycle air conditioning and anti-ice/rain removal ducts are higher, and the *cabin add heat valve* does not need to open itself as much. Basically, air does not need as much heating before it is directed to the cabin.

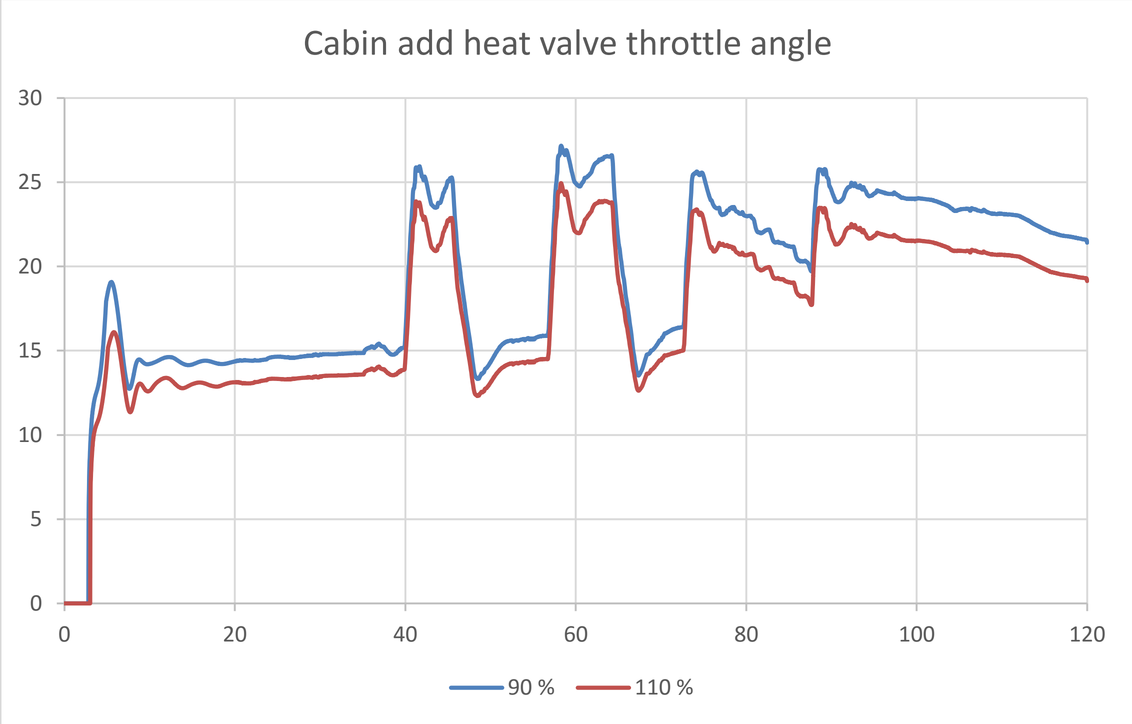

Figure 7.2. Cabin add heat valves position with 90 % and 110 % cabin flow schedules

Changes in Figure 7.2 valve position is very small, three degrees at most. In practice, such a small change is barely visible for the human eye. Control current is changed between 2 to 3 mA. Cabin flow schedules' effect to valve position and control current can be considered to be very small.

To conclude, a simulation model provides deeper knowledge of the ECS characteristics. Before, we were not able to estimate conditions inside the system during flight. Now all the aspects can be observed and the interactions between them can be unraveled. The simulation model gives information that can be considered accurate to some degree.

7.2 Study of dynamic behaviour

As mentioned in the previous chapter, the simulation model's dynamic response does not represent reality very well. Nevertheless, system characteristics can be studied to some extent. The simulation model essentially provides clarity to the complex valve interactions. ECS dynamic behaviour is much easier to understand when the valve positions, temperatures, pressures and mass flow rates can be viewed simultaneously. However, at this stage results are very speculative and have to be treated only as guidance. It may be that dynamic response is impossible to simulate with the available knowledge and the next example illustrates how far we are from the ideal simulation model.

In Figure 7.3 complex interactions of the multiple valves are shown. Four of the most influential valves' positions are plotted to the same picture which gives an idea of the correspondence between valves. Example is from the same situation as the section 6.4 example (45,000 feet, rapid throttle alternation).

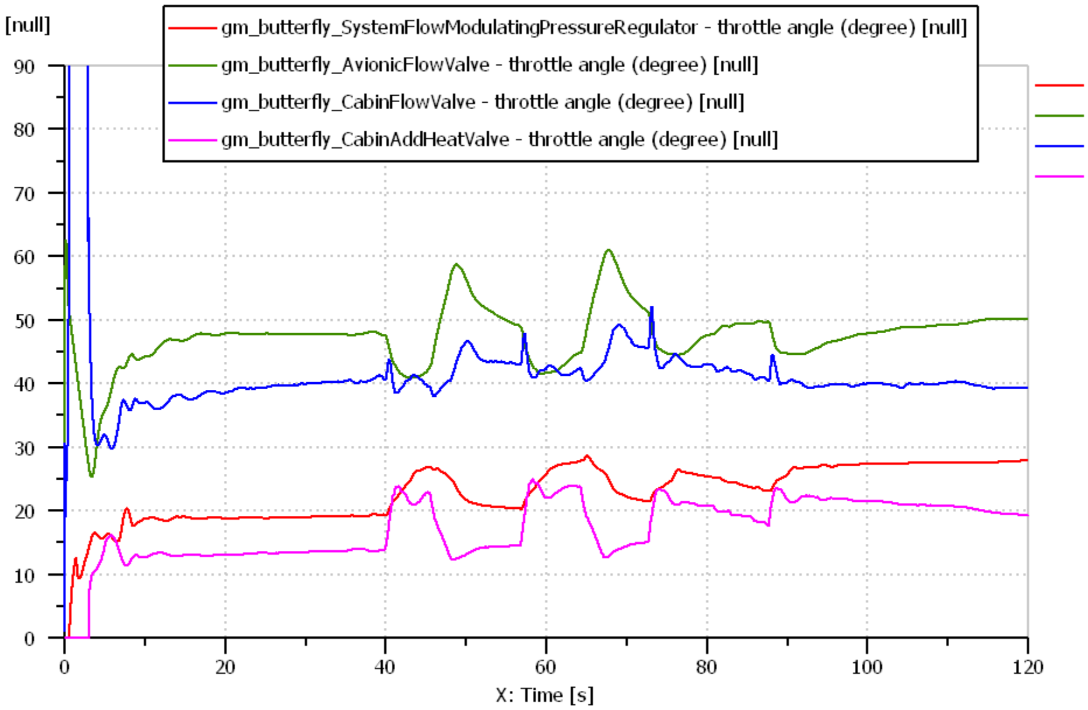

Figure 7.3. Valves' dynamic response during throttle alternation at 45,000 feet altitude

As can be seen in Figure 7.3 ECS is very stable before supply pressure drops (watch Figure 6.4. 40 second mark). Immediately after pressure plummets the *avionic flow valve* start to close so that enough air is directed to the cabin. Simultaneously, the *cabin flow valve* immediately moves towards open so that mass flow rate to the cabin stays constant. But because the *cabin add heat valve* also moves towards open, the *cabin flow valve* must move back towards closed position soon after. As the *avionic flow valve* moves towards closed position, the *system flow modulating pressure regulator* starts to move towards open in order to compensate the decrease in mass flow to the avionic plenum. When supply pressure is low, surprisingly *avionic flow valve* remains in a more closed position even though mass flow to the avionics is still too low. The *system flow modulating pressure regulator* simply does not open fast enough to satisfy both cabin and avionics flow. Cabin flow rate does not change but avionic flow rate on the contrary decreases significantly. Before the system has stabilized, meaning temperatures and mass flow rates are desirable, supply pressure already starts to rises sharply (45 second mark). Pressure rises which results in higher mass flow and this finally forces the *avionic flow valve* to a more open position. *Avionic flow valve* eventually even overshoots because the *system flow modulating pressure regulator* again reacts to the change slowly. The whole system finds stability right before the second pressure drop occurs (57 second mark).

At this point we have only observed valve positions and how valves interact. In order to fully comprehend what is truly happening, we must go even deeper. One of the most influential aspects is temperature. For example, the *anti-ice add heat valve* must react to changes in pressure and also to the decrease in temperature. As a result, the valve must open considerably more in order to keep temperature constant when pressure decreases sharply. Unless the *warm air temp control valve* manages to keep temperature in rain removal ducts constant, the *anti-ice add heat valve* also faces a similar situation as the *cabin add heat valve*.

Undoubtedly, a rapid change of cabin flow rate causes pressure fluctuations in the cabin, but the *cabin pressure regulator* and the *cabin exit air valve* also have a significant effect. From the Figure 7.4 it can be seen that a pressure peak and the opening of these valves match on the timeline. From the figure it can be concluded that the faster the *cabin pressure regulator* and *cabin exit air valve* react, the smaller the change in cabin pressure.

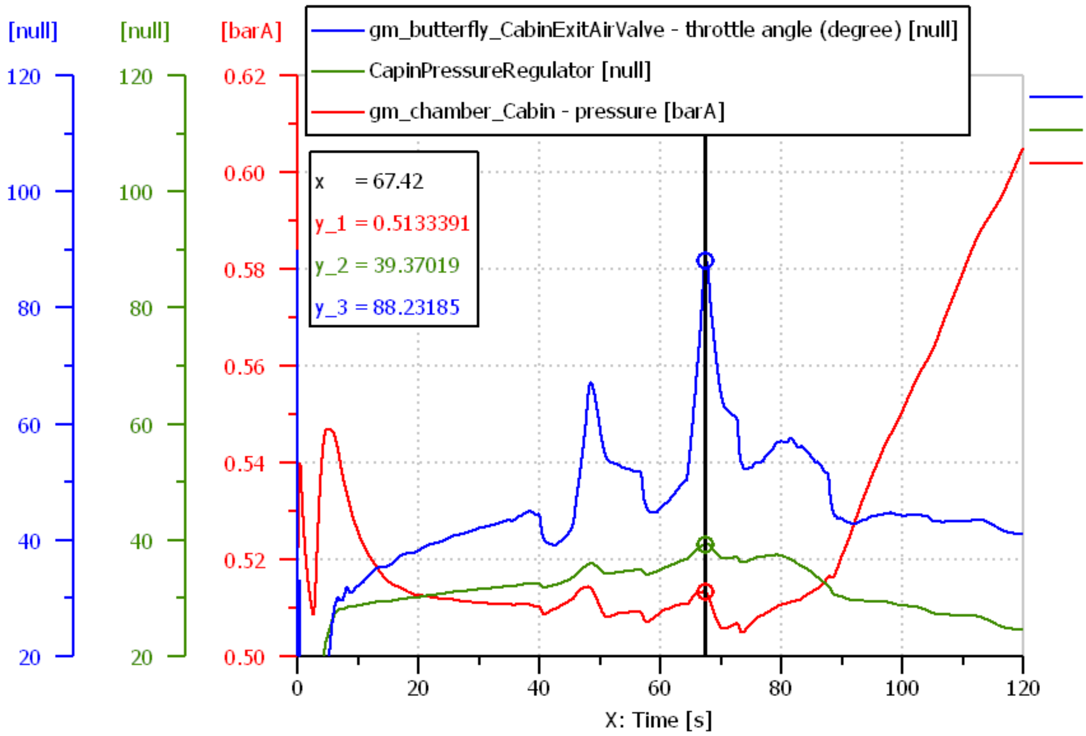

Figure 7.4. Pressure surges effect to cabin pressure regulator and cabin exit air valve

Figure 7.4 shows that the *cabin pressure regulator* and *cabin exit air valve* both affect the cabin pressure. Basically, the *cabin exit air valve* regulates the pressure in the space right after the *cabin pressure regulator*. So the more the *cabin exit air valve* opens, the more the pressure decreases and the greater the pressure difference over the *cabin pressure regulator*. It may be that the *cabin exit air valve* makes controlling the cabin pressure faster since the *cabin pressure regulator* does not need to open as much and as rapidly. However, if the pressure surge is very large, the *cabin exit air valve* cannot solely decrease pressure in the cabin and the *cabin pressure regulator* also needs to move in order to increase mass flow rate through it. How exactly these two valves work together is still under investigation.

In conclusion, the simulation model helps troubleshoot the complex interactions and gives new ways to study system. As illustrated above, without simulations evaluation of the ECS characteristics would be troublesome if not impossible. Now every single parameter in the model can be adjusted and effects are seen immediately after a new simulation run.

7.3 Future simulation studies

At this point, one cannot say what the limits of the future simulation model will be. With confidence it can be stated that static situations can be simulated accurately enough but dynamic simulations may be unreliable. Next multiple future interests are discussed.

It has been suspected that fouled flow sensors in the avionic plenum may increase tendency of unstable behaviour of the ECS. Basically, a fouled sensor causes increase of the mass flow rate which in turn may cause problems. With an improved model it could be tested whether the mass flow can increase so much that the *avionic flow valve* cannot compensate the pressure surges by opening itself. In other words, when the *avionic flow valve* is not able to pass through enough extra mass flow and therefore keep the pressure over the *cabin flow valve* constant.

Another interest is the manual mode. Especially, how much mass flow increases in manual mode and what kind of effect it has. Also, a more demanding simulation case would be the study of dynamic responses during manual-mode.

In addition, the simulation model could be used to evaluate effects of one or multiple component failures. For example, it could be studied how a jammed valve affects ECS and pilot safety. Similarly, sensor failures can be examined.

8. CONCLUSION

In this thesis a complex simulation model of the ECS was constructed in order to study system characteristics, improve robustness and acquire a more profound understanding of the system. A model-based approach was chosen since other techniques could not be used to acquire required knowledge. Whereas measurements and observation could be utilized during ground testing, these methods were impossible to implement during flight. In fact, ECS was discovered to be most unstable at high altitudes and the simulation model provided one of the best ways to study its causes further.

Multiple former researches have used the model-based approach successfully as the literature review argued. Almost every single aspect of the ECS's components have been modelled at least at an individual level, and multiple studies also simulated assemblies comprising multiple submodels. However, simulation studies of the entire system's dynamic response were hard to find. It may be that most of the research is not available publicly. Despite the lack of published research similar to this thesis, it is likely that a model-based approach can be used to acquire more knowledge of the ECS.

During simulation model development the working principle of ECS was studied thoroughly. All of the available data was examined and the most qualified personnel from the air force took part in the development process. Data used comprises the aircraft manuals, aircraft testing procedures, interviews, measurements and direct visual examinations. All the information collected was then used during modeling and simulation.

The actual simulation model was constructed to be as simplified as possible. Great effort was put to decreasing simulation time and complexity. Only the most crucial systems were modelled so that simulation time would not increase drastically and in order to simplify the difficult verification process. Also, model expandability was considered and modifications to the simulation model are easily implemented.

Verification and validation results of the model were promising. Consequently, it seems that the model can be utilised to study the most common flight situations. However, models accuracy decreases greatly when aircraft velocity is either low or high. Also, low altitudes decrease accuracy due to the ram air scoop model's simplistic fluid mechanics and increase of ambient air humidity. Moreover, the model of the avionic plenum cannot be considered accurate during flight, even though results were virtually prefect at sea level. Ultimately, more measurements are required in order to further verify the models accuracy.

During this thesis the ultimate goal was not achieved. With the simulation model ECS dynamic response could not be studied reliably. Simulation experiments helped to understand the interactions of the valves, but the results did not provide unambiguous reasons for the dynamic response phenomena observed empirically. Much further research is needed so that clear conclusions can be drawn from the simulation results. However, it may be near impossible to achieve an accurate level of modeling because of the severe complexity of the system.

The simulation model presented in this thesis is yet incomplete. Many open questions still remain that are essential for an accurate model. Some future measurements may provide additional knowledge of the conditions inside ECS that finally lead to an improved model. However, the model will most certainly always be a simplified version of the real-world phenomena and therefore will have many limitations.

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APPENDIX A: ISOMETRIC VIEW OF PASSENGER AIRCRAFT ECS STRUCTURE

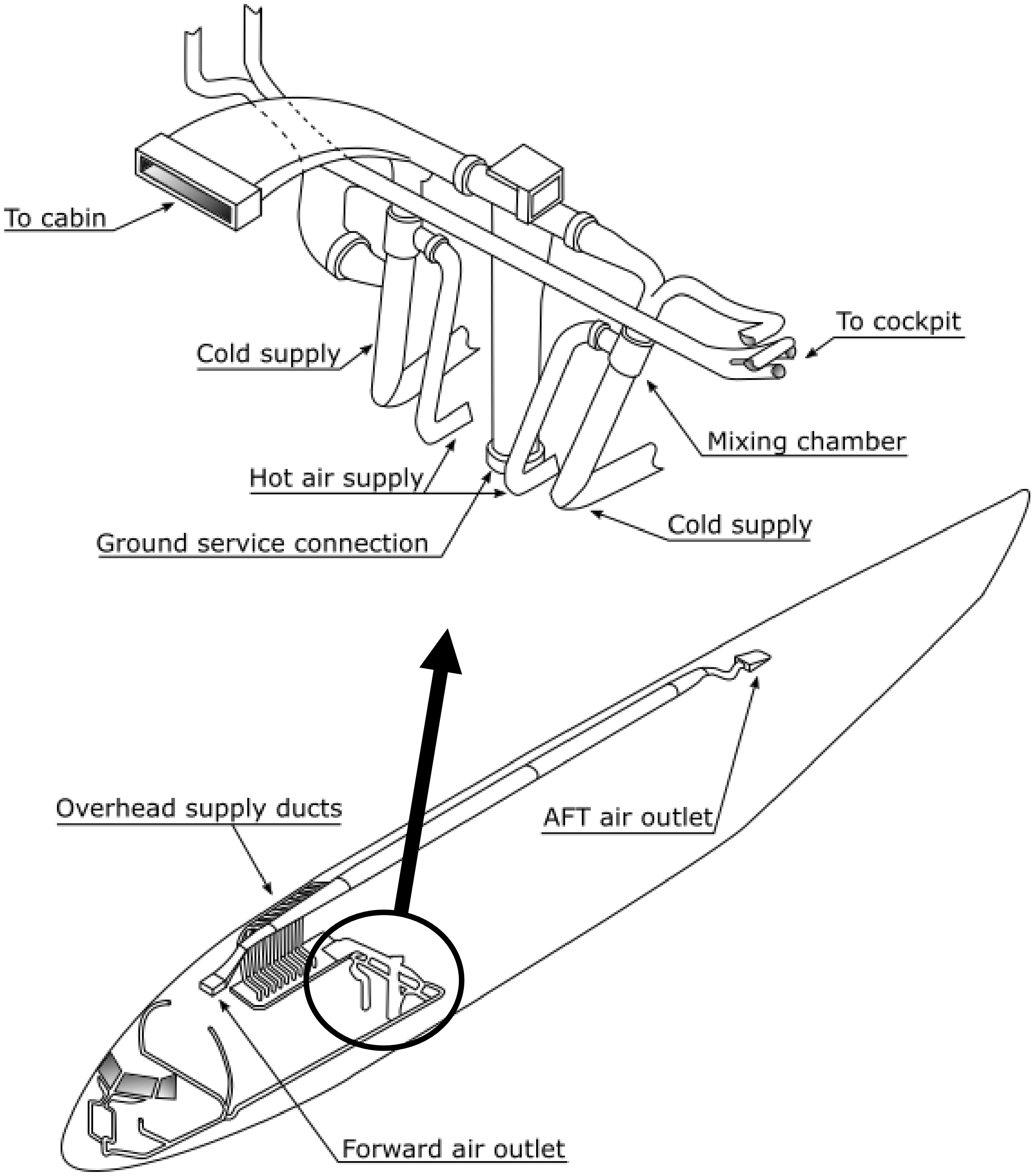
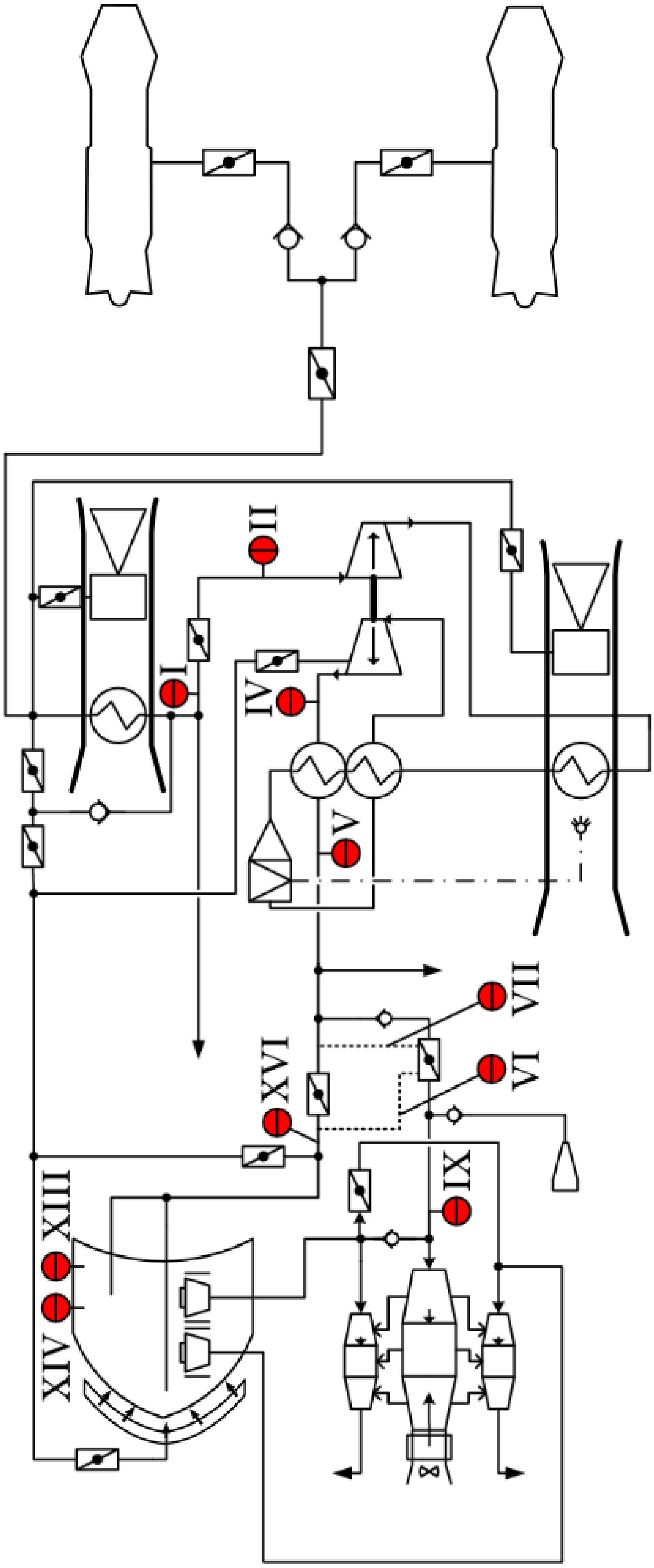
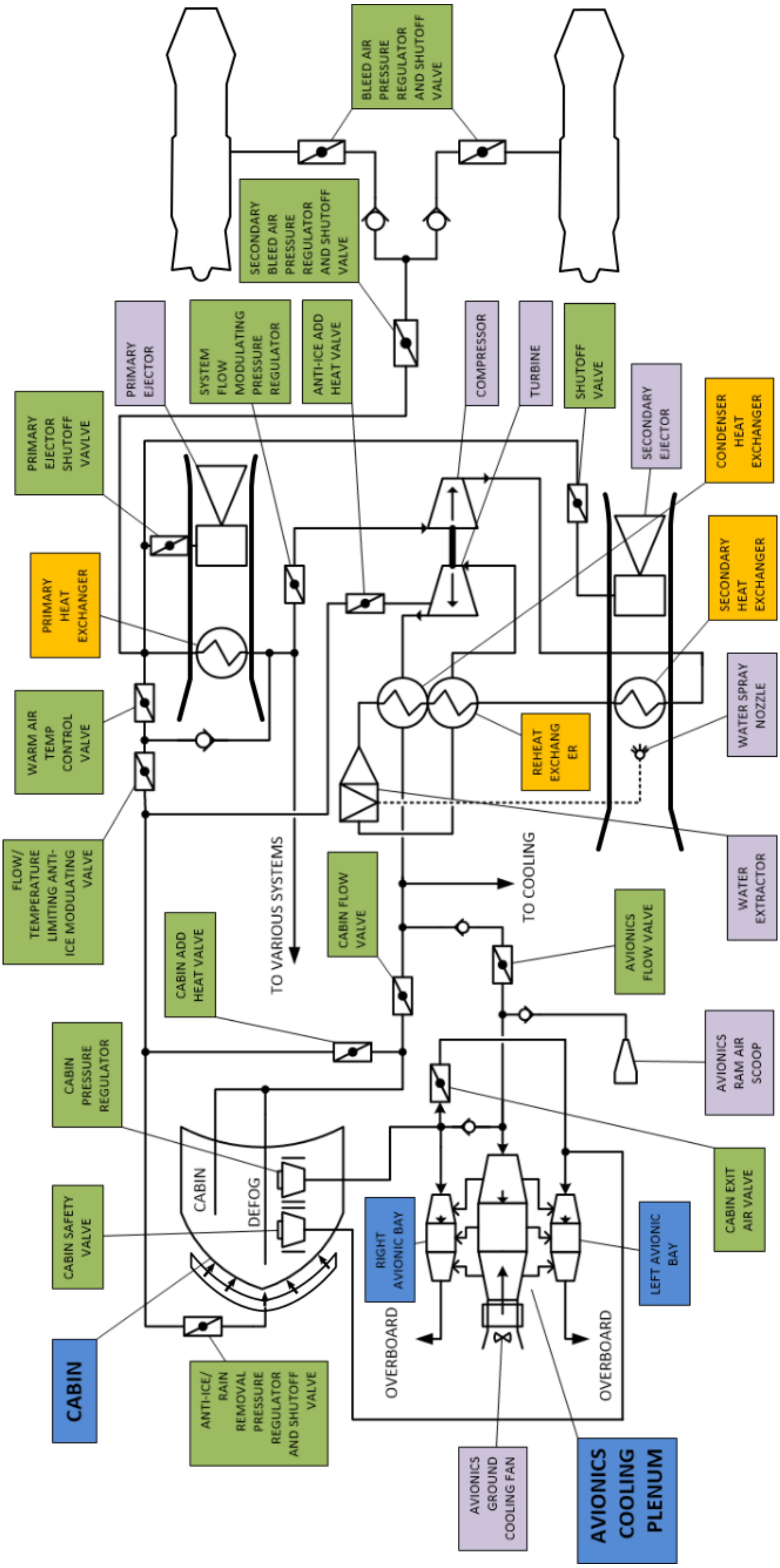


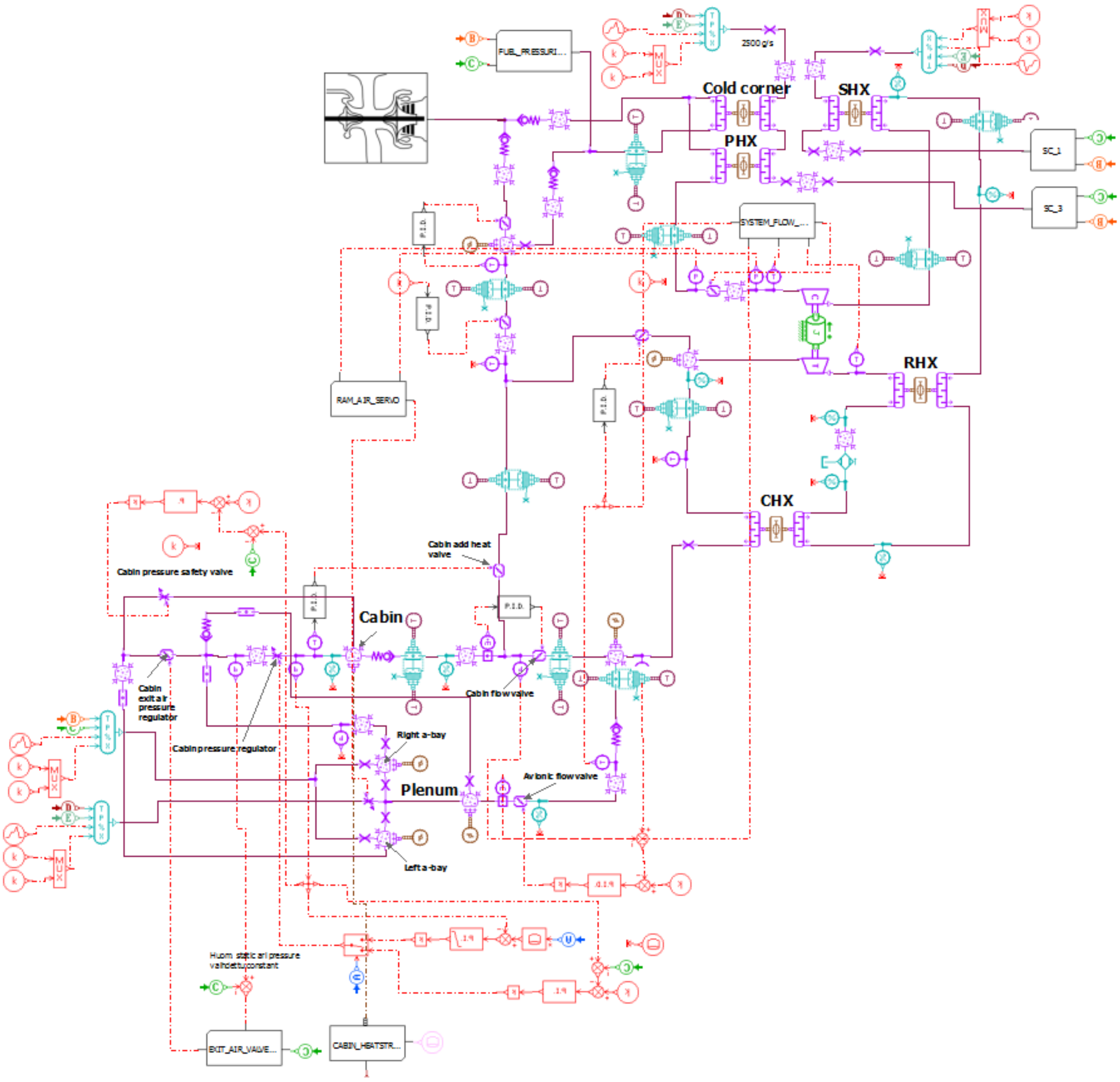
Figure adapted from [26].

APPENDIX B: SCHEMATICS OF THE MODELLED ECS



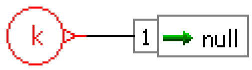
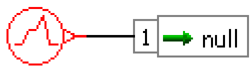
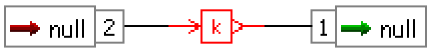
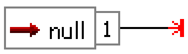
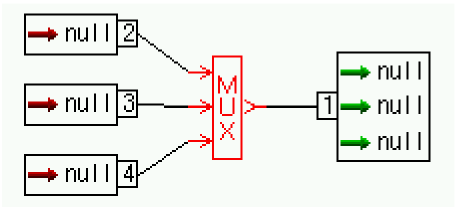
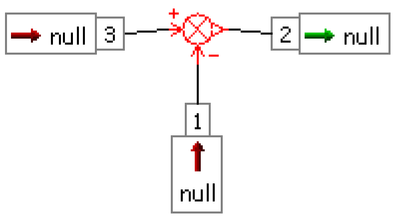

BLEED AIR PRESSURE REGULATOR AND SHUTOFF VALVE
SECONDARY BLEED AIR PRESSURE REGULATOR AND SHUTOFF VALVE
PRIMARY EJECTOR
SYSTEM FLOW MODULATING PRESSURE REGULATOR
ANTI-ICE ADD HEAT VALVE
COMPRESSOR
TURBINE
SHUTOFF VALVE
SECONDARY EJECTOR
CONDENSER HEAT EXCHANGER
PRIMARY EJECTOR SHUTOFF VAVLVE
PRIMARY HEAT EXCHANGER
SECONDARY HEAT EXCHANGER
WATER SPRAY NOZZLE
WARM AIR TEMP CONTROL VALVE
REHEAT EXCHANG ER
FLOW/ TEMPERATURE LIMITING ANTI-ICE MODULATING VALVE
TO VARIOUS SYSTEMS
CABIN FLOW VALVE
TO COOLING
WATER EXTRACTOR
AVIONICS FLOW VALVE
CABIN ADD HEAT VALVE
CABIN PRESSURE REGULATOR
AVIONICS RAM AIR SCOOP
CABIN
DEFOG
CABIN EXIT AIR VALVE
RIGHT AVIONIC BAY
LEFT AVIONIC BAY
CABIN SAFETY VALVE
OVERBOARD
OVERBOARD
CABIN
ANTI-ICE/ RAIN REMOVAL PRESSURE REGULATOR AND SHUTOFF VALVE
AVIONICS GROUND COOLING FAN
AVIONICS COOLING PLENUM

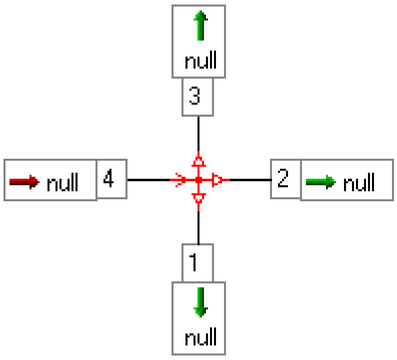
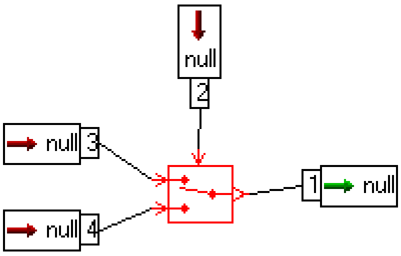
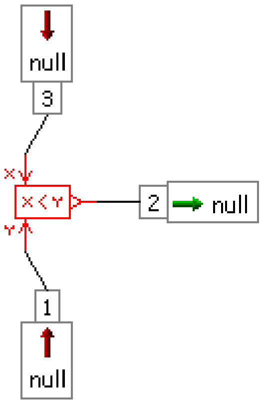
APPENDIX C: COMPLETE AMESIM MODEL

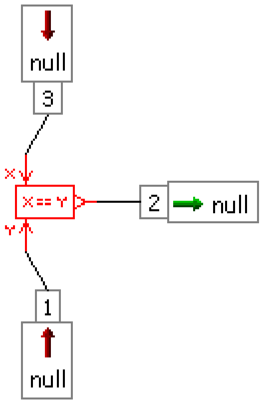
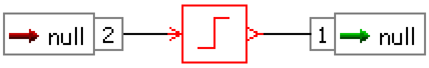
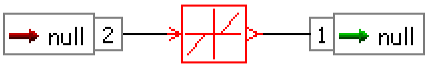
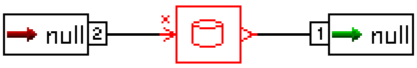
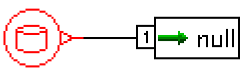
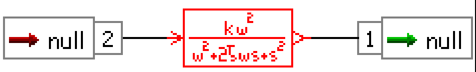


APPENDIX D: AMESIM SUBMODELS [40]

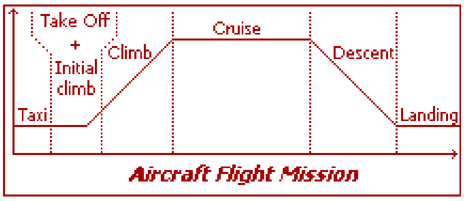
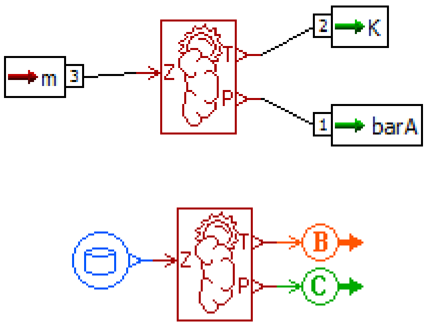
Signal, Control library

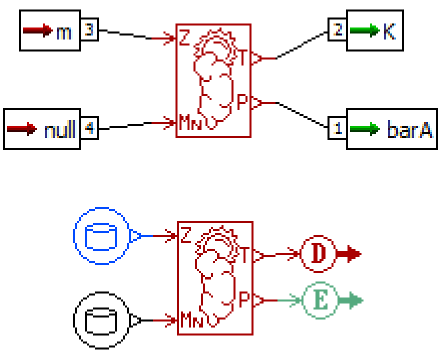
	**CONS00** outputs a signal with a constant specified value
	**UD00** is a duty cycle submodel with a dimensionless output. The user may specify up to 8 stages giving a start value, an end value and the duration for each stage. Linear interpolation is used to determine the output. Thus constant sections, ramps and steps may be constructed.
	**GA00** is a gain. The output signal at port 1 is formed by multiplying the input signal at port 2 by a user specified gain.
	**SSINK** exists solely to plug a signal port.
	**DYNMUX2** is a multiplexer. It combines the variables of its multiple (left) input ports into a single (right) output port. The number of input ports is dynamic because it is set by the user when the icon is selected. The input variables can be scalars or vectors. **DYNMUX2** offers multiple possibilities for grouping the input variables into scalars or vectors to the output port.
	**JUN3M** is a 3 port subtracting junction. The output signal at port 2 is the difference between the input signals at ports 1 and 3.

	**SPLT1** is a submodel used to split an input signal into 3 identical outputs. The signal input to port 4 is split and output without modification on ports 1, 2 and 3.
	This submodel produces an output that switches from one value (input at port 4) to another one (input at port 3) when the command switch (input at port 2) is above or equal to the user supplied threshold. The output switches from the value at port 3 to the one at port 4 when the command signal drops below the threshold : output = input3 when command ≥ threshold output = input4 when command < threshold
	**PID001** is a PID controller, which output v is of the form $v = Kp.u + Ki.\int_{t_{start}}^{t} u.dt + Kd.\frac{\partial u}{\partial t}$ The output signal v can optionally be limited by a minimum and maximum value. **PID001** can either work in PID, PI, PD or P modes.
	**LT00** makes a comparison between the inputs x and y and returns a signal of value 1 if x < y 0 and 0 if x ≥ y .

	**EQ00** makes a comparison the inputs x and y and returns a signal of value 1 at port 2 if x = y and 0 in any other case.
	**SW00** generates an output that switches from a one value (the low value) to another value (the high value) when the input is above a user supplied threshold. The output switches back to the low value when the input signal drops below the threshold.
	**DEAD0** is a submodel of a dead zone between two user specified values for the input x . When the input is between xmin and xmax , the output y is set to 0. Outside this range, the output is computed as the input value minus an offset corresponding to the nearest limit of the interval where y is null.
	**SIGFXA01** reads a 1D or XY table and interpolates data as functions of input x. The interpolation can be either linear or cubic. The number of outputs is defined by the user: in case of multiple outputs, each output signal ui(x) corresponds to a column of the XY table. Note that the number of outputs can differ from the number of columns of the XY file.
	**SIGUDA01** reads a 1D or XY table and interpolates data as functions of time u(t). The interpolation can be either linear or cubic. The number of outputs is defined by the user: in case of multiple outputs, each output signal ui(t) corresponds to a column of the XY table. Note that the number of outputs can differ from the number of columns of the XY file.
	**LAG2** is a 2nd order lag of the form $\dfrac{k.w^2}{w^2 + 2.z.w.s + s^2}$

Aeronautics & Space library

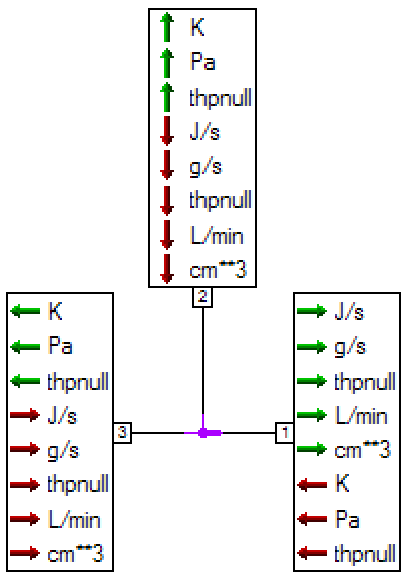
<table>
<tr>
<td>
</td>
<td>This component allows the definition of a flight mission from its flight phases, their duration and the associated aircraft Mach number and altitude.
Can be used if the measured data from flight is not available or when testing the imaginary situations. Output values based on the International Standard Atmosphere 1976.</td>
</tr>
<tr>
<td>
</td>
<td>This submodel is the implementation of the standard atmosphere model known as ISA-1976. This model has been built on a set of measurement done during the 70's and since this time is the reference one to get the properties of air (temperature, pressure, density, sound-speed...) as a function of altitude. This model is identical to the U.S. Standard Atmosphere 1976 for altitudes below 86 [km]. It is also identical to the COESA Atmosphere model as well as to the Standard Atmosphere of the ICAO (International Civil Aviation Organization) below 32 [km].

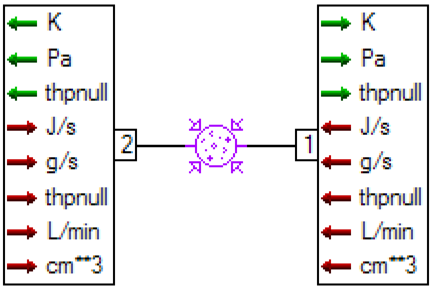
Measurements of the flight altitude can be utilized as an input. Then submodel calculates temperature and static pressure. Values can be asily distributed for the simulation model using dynamic transmitter.</td>
</tr>
<tr>
<td>
</td>
<td>The ATBATM_ISA02 model is the implementation for standard atmosphere model known as ISA-1976. This model has been built on a set of measurements done during the 70's and since this time is the reference one to get the air properties (temperature, pressure, density) as a function of altitude. This model is identical to the U.S. Standard Atmosphere 1976 for altitudes below 86 [km]. It is also identical to the COESA Atmosphere model as well as to the Standard Atmosphere of the ICAO (International Civil Aviation Organization) below 32 [km].

This model allows the computation of total air temperature (TAT) and pressure (TAP) that depend not only on the altitude but also on the Mach number. Values can be easily distributed for the simulation model using dynamic transmitter.</td>
</tr>
</table>

	Transfers some variables to one or several receiver submodels without any visible connection on the sketch. A transmitter and a receiver behave as if the output of the transmitter is connected to the input of the receiver. As a result, the receiver output is actually a duplicate of the transmitter input. However this connection is not visible on the sketch since these two components are not directly connected and are not linked by any line. Submodels are color- and letter-marked.
	Receives variables from a transmitter submodel without any visible connection on the sketch. A transmitter and a receiver behave as if the output of the transmitter is connected to the input of the receiver. As a result, the receiver output is actually a duplicate of the transmitter input. However this connection is not visible on the sketch since these two components are not directly connected and are not linked by any line. Submodels are color- and letter-marked.

Gas mixture library

	This submodel is a 3-port gas mixture junction with temperature, pressure and species concentrations fixed by port 1. The bold line indicates from which port pressure and temperature are imposed to the submodel. The derivatives of volume and chamber volumes are required as inputs on ports 2 and 3 in addition to the enthalpy and mass flow rates. The pressure, temperature and species concentrations are fixed by port 1. The enthalpy flow rates, the mass flow rates, the derivatives of volume and chamber volumes are summed and passed as outputs to port 1.

<table>
<tr>
<td>


</td>
<td>
This is a submodel of gas mixture chamber with variable volume and pressure dynamics.

Mass flow rate [g/s], enthalpy flow rate [J/s], index of chamber [thpnull], derivative of volume [L/min] and volume [cm**3] are inputs at each pneumatic port and pressure [Pa], temperature [K] and index of the chamber [thpnull] are returned as outputs.

The balance for each species is computed with the chamber index of each incoming flow rate. It refers to the upstream volume and allows to access to the concentration of the mixture flow rate.

This model is utilized for mixtures with up to 20 gases and the species initial fractions can be given either as molar or mass fractions.
</td>
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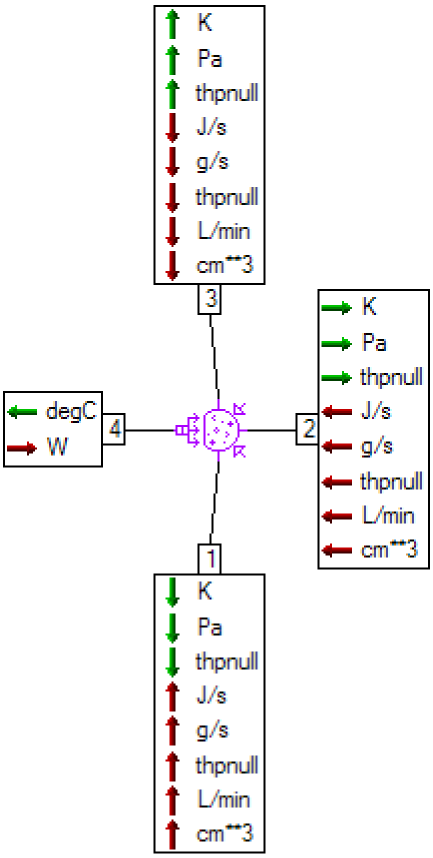
<td>


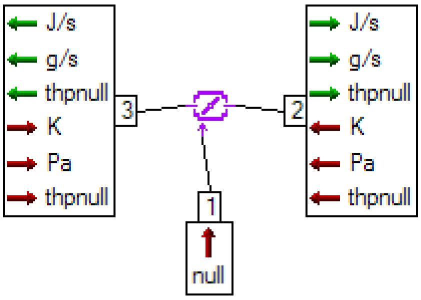
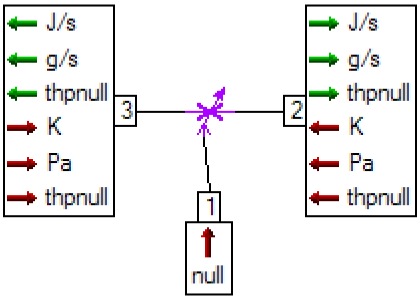
</td>
<td>
This is a submodel of gas mixture chamber with variable volume, pressure dynamics and heat exchange.

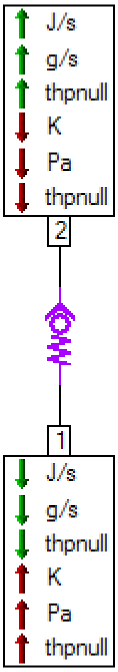
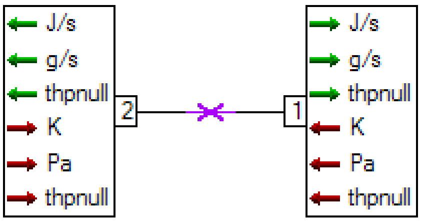
Mass flow rate [g/s], enthalpy flow rate [J/s], index of chamber [thpnull], derivative of volume [L/min] and volume [cm3] are inputs at each pneumatic port and pressure [Pa], temperature [K] and index of the chamber [thpnull] are returned as outputs.

The balance for each species is computed with the chamber index of each incoming flow rate. It refers to the upstream volume and allows to access to the concentration of the mixture flow rate.

The user can impose a heat flow rate in the chamber through thermal port 4.

This model can be used for mixtures with up to 20 gases and the species initial fractions can be given either as molar or mass fractions.
</td>
</tr>
</table>

	This is a submodel of a gas mixture butterfly valve. Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at ports 2 and 3 and mass flow rate in [g/s], enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at ports 2 and 3. Mass and enthalpy flow rates in the component are computed from temperatures and pressures at port 2 and 3, from the throttle angle at port 1 and from gas mixture properties at component inlet. The throttle angle [degree] is provided as an in-put at port 1 (signal port).
	This is a submodel of a gas mixture orifice with a variable area. Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at both ports and mass flow rate in [g/s],enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at both ports. The discharge coefficient Cq is constant.

	This is a simple submodel of a gas mixture relief valve. Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). A pressure in [Pa], a temperature in [K] and a node index [thpnull] are inputs at each port and a mass flow rate in [g/s], an enthalpy flow rate in [J/s] and a node index [thpnull] are computed to be outputs at both these ports. No dynamics are incorporated. The discharge coefficient Cq is calculated with Perry's polynomial. The flow goes from port 2 to port 1 if the pressure at port 2 is greater than the sum of the cracking pressure and the pressure at port 1. GMCV001 incorporates mild hysteresis so that the check valve opens a little above its nominal cracking pressure and closes a little below the cracking pressure. The default value of this hysteresis is zero. If the check valve `chatters', i.e. opens and closes rapidly, many discontinuities will be produced leading to a slow run.
	This is a submodel of gas mixture orifice with a constant area. The discharge coefficient Cq is constant and set by the user. Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at both ports and mass flow rate in [g/s],enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at both ports.

<table>
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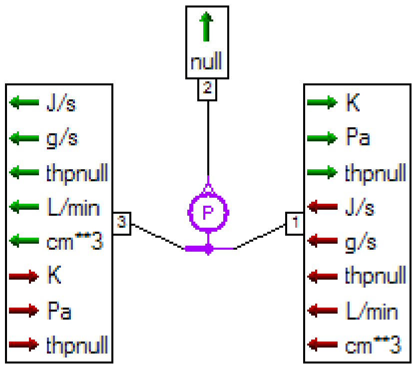
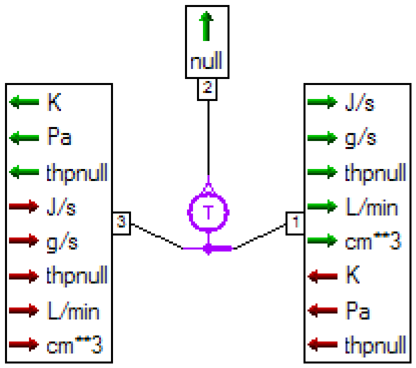
<td>
</td>
<td>This is a submodel of a gas mixture pressure transducer.

Pressure [Pa], temperature [K] and chamber index [thpnull] inputs at port 3 are passed without modification to be outputs at port 1.

The bold line indicates from which port pressure and temperature are imposed to the submodel.

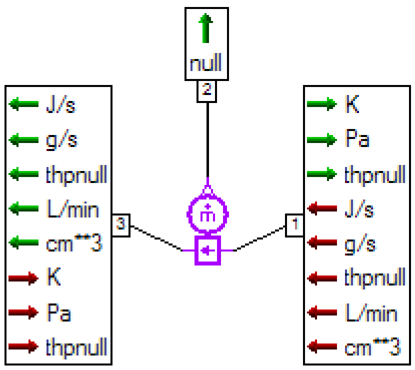
Mass flow rate [g/s], enthalpy flow rate [J/s], chamber index [thpnull] derivative of volume [L/min] and volume [cm3] inputs at port 1 are passed without modification to port 3.

The pressure is converted into an absolute pressure [BarA]. An offset [bar] is subtracted from this pressure and the result is multiplied by a gain to become a signal with null units at port 2.</td>
</tr>
<tr>
<td>
</td>
<td>This is a submodel of a gas mixture temperature transducer.

Pressure [Pa], temperature [K] and chamber index [thpnull] inputs at port 1 are passed without modification to be outputs at port 3.

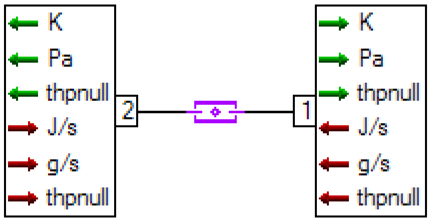
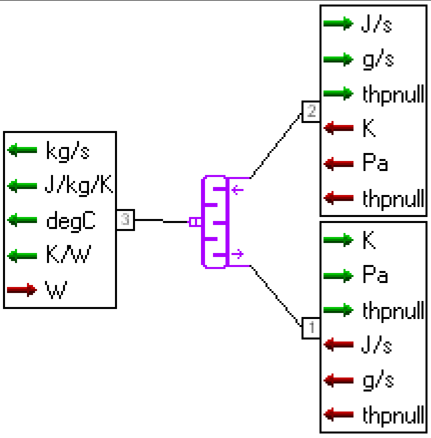
The bold line indicates from which port pressure and temperature are imposed to the submodel.

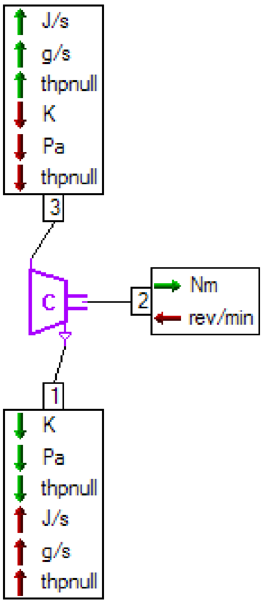
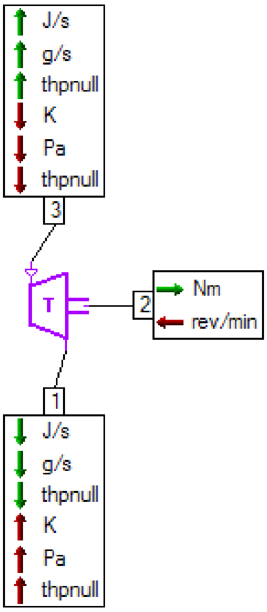
Mass flow rate [g/s], enthalpy flow rate [J/s], chamber index [thpnull] derivative of volume [L/min] and volume [cm3] inputs at port 3 are passed without modification to port 1.

An offset [K] is subtracted from the temperature and the result is multiplied by a gain to become a signal with null units at port 2.</td>
</tr>
<tr>
<td>
</td>
<td>This is a gas mixture mass flow rate transducer.

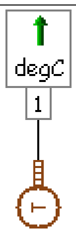
Pressure [Pa], temperature [K] and chamber index [thpnull] inputs at port 1 are passed without modification to be outputs at port 3. Mass flow rate [g/s], enthalpy flow rate [J/s], chamber index [thpnull] derivative of volume [L/min] and volume [cm3] inputs at port 3 are passed without modification to port 1.

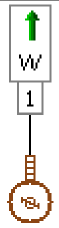
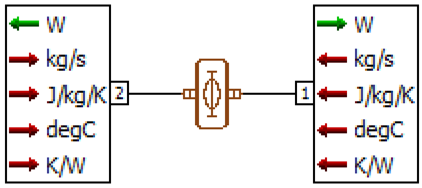
An offset [g/s] is subtracted from the mass flow rate and the result is multiplied by a gain to become a signal with null units at port 2.</td>
</tr>
</table>

	If the gain is positive, the arrow on the icon indicates the direction of a positive flow rate.
	GMDP010 is a submodel of gas mixture discretized pipe suitable for long or moderately long lines with compressibility, friction and optional inertia effects (C-(I)R-***-(I)R-C). The user has to choose between two pipe models: with friction effects only (C-R-***-R-C) with friction and inertia effects (C-IR-***-IR-C) The pipe friction is taken into account using a friction factor based on the Reynolds number and the relative roughness. The inertia and friction phenomena are taken into account on the same flow state variable. The pipe can be discretized with up to 20 elements in order to take into account pressure, temperature and mass fraction variations along the pipe. The pipe discretization is based on an interlacing grid system composed of the number of discrete elements defined by the user.
	**GMEX0010** is a submodel of a half heat exchanger which can be used to globally model a heat exchanger relying on known Nusselt correlations and wall thermal resistance. All calculations are based on the efficiency-NTU method. In this submodel fins may be considered to enhance the exchange.

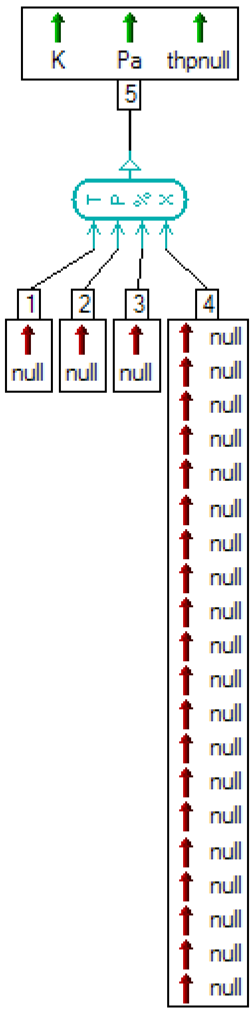
	**GMCP02** is a submodel of compressor for gas mixture applications. The user must supply two multi-1D splines look up tables for the following characteristics as function of dmc, the corrected mass flow rate in [kg/s] and wc, the corrected rotary speed of the compressor in [rev/mn] The compressor rotary speed must be positive. If the rotary speed is negative, its value is set to 0 and the other variables of the compressor such as torque and mass flow rate are also set to 0.
	**GMTB01** is a submodel of turbine for gas mixture applications. Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at both flow ports and mass flow rate in [g/s],enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at both flow ports.

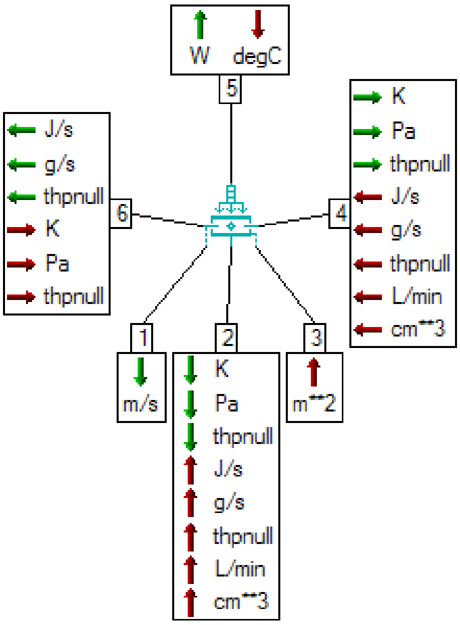
Thermal library

	**THTS1** is a constant temperature source. The temperature in degC is set by the user and is output at port 1.

	**THHS0** is a constant heat flow source in W. The user has to specify the value of the heat flow rate which is generated at port 1.
	**THPHI001** calculates the heat flow in a heat exchanger relying on known Nusselt correlations and wall thermal resistance. All calculations are based on the efficiency-NTU method. The mass of the heat exchanger can also be set in this submodel.

Moist air library

	This submodel is a modulated moist air pressure, temperature and humidity source. The submodel inputs are signals like: the temperature in [K] at port 1 the pressure in [barA] at port 2 the humidity in [%] at port 3 the dry air fractions [null] at port 4 (multiplexed signal). The submodel outputs at port 5 are the pressure in [Pa], the temperature in [K] and the communication index [thpnull].



MAP000 is a submodel of moist air pipe with heat exchange, friction and optional inertia effects ((I)R - C).

The user has to choose between two pipe models:

with friction effects only (R - C)
with friction and inertia effects (IR - C)

Port 1 returns the moist air mean velocity through the pipe [m/s] as output.

Liquid/wall exchange area [m] is provided at port 3.

Like in all gas mixture R or IR components, the gmr or gmir utility functions manage the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at port 6 and mass flow rate in [g/s],enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at port 6.

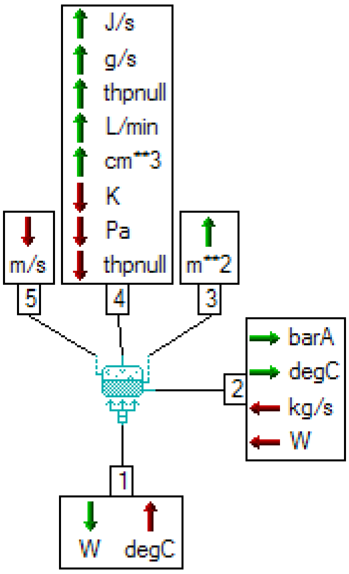
Port 4 (corresponding to the capacitive element) receives a mass flow rate [g/s], an enthalpy flow [J/s] rate, an index of chamber [thpnull], a derivative of volume [L/min] and a volume [cm3] as inputs and returns the pressure [Pa], the temperature [K] and the index of the chamber [thpnull] as outputs.

Port 2 has the same causality as port 4 and can be used to plug specific components to the pipe, such as a condensation submodel MACND010.

The pipe friction is taken into account using a friction factor based on the Reynolds number and the relative roughness.

The inertia and friction phenomena are taken into account on the same flow state variable.

External exchange is computed at port 5: it combines convective and radiative exchanges between the gas mixture circulating in the pipe and the wall of the pipe.

<table>
<tr>
<td>
</td>
<td>This submodel is a moist air homogeneous condensation/vaporization chamber.

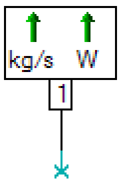
Port 1 is a thermal port which receives the wall temperature [degC] as input and returns the heat flow [W] provided to the wall from the liquid as output.

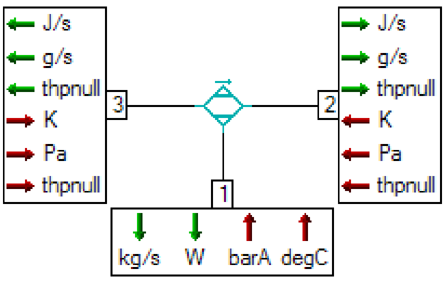
Port 2 is a thermal-hydraulic port which allow the user to remove/inject liquid water from/into the chamber.

Liquid/wall exchange area [m] is returned at port 3.

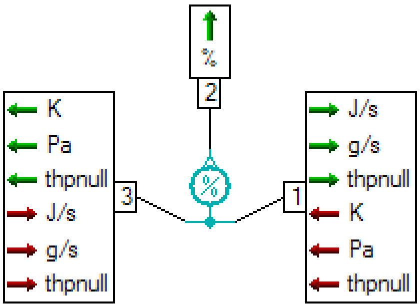
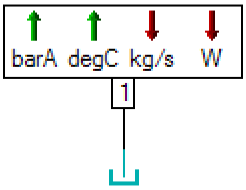
This submodel can be plugged to any gas mixture or moist air capacitive element in order to model the phase changes between liquid water and water vapour occurring in it. Port 4 receives pressure [Pa], temperature [K] and index of the chamber [thpnull] as inputs and returns mass flow rate [g/s], enthalpy flow rate [J/s], index of chamber [thpnull], derivative of volume of liquid [L/min] and volume of liquid [cm3] as outputs.

Port 5 recieves the relative mean velocity between moist air and liquid water in the capacitive element [m/s] as input.

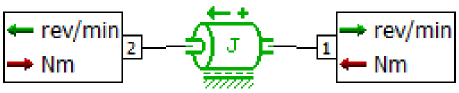
Notes:
liquid phase is not transported through the chamber but remains in it.
condensation at chamber wall is not accounted for in this submodel.</td>
</tr>
<tr>
<td>
</td>
<td>This is a submodel of a zero mass flow rate and zero enthalpy flow rate plug.

The mass flow rate and the enthalpy flow rate which are outputs at port 1 are set to zero.</td>
</tr>
<tr>
<td>
</td>
<td>This is a submodel of moist air dryer (R) using expressions or characteristic tables.

The aim of this component is to remove part of the inlet water vapour (port 3) from the air stream. The removed water vapour mass flow rate is transformed into liquid water and is drained out at port 1 (thermal-hydraulic port).</td>
</tr>
</table>

	Like in all gas mixture resistive components, the gmr utility function manages the choice of the upstream chamber that flows in the element (flow direction management). Pressure in [Pa], temperature in [K] and node index [thpnull] are inputs at both pneumatic ports 2 and 3, and mass flow rate in [g/s],enthalpy flow rate in [J/s] and node index [thpnull] are the computed outputs at both ports.
	This is a submodel of moist air humidity transducer. Pressure in [Pa], temperature in [K] and node index [thpnull] inputs at port 1 become outputs at port 3 without modifications. Mass flow rate in [g/s], enthalpy flow rate in [J/s] and node index [thpnull] inputs at port 3 become outputs at port 1 without modifications.
	This is a submodel of a thermal-hydraulic tank. The tank is regarded as a constant pressure and temperature source, respectively in barA and in degC.

Mechanical library

	**RL01** is a simple dynamic submodel of a rotary load under the action of two external torques in Nm applied to its two ports. There is provision for viscous friction, Coulomb friction and stiction. RL01 computes the rotary velocity in rev/min. The rotary acceleration is computed as an internal variable.