Modelling of a Generic Aircraft Environmental Control System in Modelica

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by

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Abstract

This thesis documents the modelling of generic Environmental Control System (ECS) of an aircraft in Modelica by utilizing components from free version of the TTECCS (Technical Thermodynamic Environmental Control and Cooling Systems) library. In doing so, components used for developing ECS from the TTECCS library are mathematically verified with theoretical formula in MATLAB. Selected components are investigated with valid input data to initialize the simulation and verify its behaviors with corresponding available data.

Hereinafter, the object-oriented modelling method is used to integrate ECS components to develop a functional system. The main function of ECS is to regulate the pressure and temperature inside the cabin to accepted physiology flight safety levels. Different types of ECS architecture are presented in this document. An ECS developed here is based on the bootstrap system and consists only one cooling unit comprised with the source, pipes, two heat exchanger, compressor, turbine, temperature control valve, pressure control valve, and sinks. Dry air(Ideal gas) is used as a medium in the system. Temperature drop along each component corresponds to available A320 cruise flight data in order to calculate the top level parameter and to initialize the components, subsequently an ECS system.

Several systematized methods for Object-oriented modelling and system design were studied and steps are extracted accordingly that suits to initiate the procedure for this project, which is also presented. Time domain simulation is performed in Modelica and Dymola. A simplified control system is built to regulate the system, therefore restrained it as a future work to develop real in-flight condition control system of an ECS.

Top level parameters were selected within valid customized ranges for developing a performance map of the components. After generating the map, optimal data from the map were taken to initialize final ECS. The simulation results of the final model is then compared to A320 flight data which is comparable in behavior; this was expected.

Above all, simulation environment Modelica and free version of TTECCS library components are reliable to develop ECS in order to investigate ECS components behavior and predict cabin conditions before developing a prototype.

Acknowledgements

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Finally, I express my profound gratitude to my parents and my brother for providing immense support all the time. Thank you

Nomenclature

Abbreviations and Acronyms

Abbreviation	Meaning
ECS	Environmental Control System
SBE	Simulation Based Engineering
TTECCS	Technical Thermodynamic Environmental Control and Cooling Systems
ECU	Environmental control Unit
ACS	Air condition system
WAV	Wing anti-ice valve
APU	Auxiliary power unit
ISA	International standard atmosphere
PHX	Primary heat exchanger
MHX	Main heat exchanger
OOM	Object oriented modeling
OOP	Object oriented programming
ANTLR	Another tool for language recognition
GUI	Graphical user interface
MSL	Modellica standard library
LTS	Liebherr Aerospace Toulouse S.A.S

Latin Symbols

Symbol	Description	Units
A	Surface area	$\left[m^2\right]$
c	Heat capacity	$\left[Wm^{-2}K^{-1}\right]$
p	Pressure	$[Pa]$
t	Time	$[s]$
q	Heat transfer rate	$[s]$
U	Mean velocity	$[msec^{-}1]$
T	Temperature	K
S	Sutherland Temperature	K
M	Mach number	
$\dot{m}$	Mass flow rate	$[kgsec^{-}1]$
D	Hydraulic diameter	$[m]$
W_p	Wetted perimeter	$[m]$
L	Length	$[m]$
K	Overall system loss coefficient	
w	Gas flow rate	$[lb/h]$
$\vec{C}$	Absolute velocity	$[msec^{-}1]$
$\vec{U}$	Rotational velocity	$[msec^{-}1]$

Symbol	Description	Units
$\vec{R}$	Relative velocity	$[msec^-1]$
Re	Reynold number	

Greek Symbols

Symbol	Description	Units
α	Angle	$[degree]$
μ	Dynamics viscosity	$\left[kgm^{-1}s^{-1}\right]$
π	Pressure ratio	
ω	Rotational speed of shaft	$\left[radsec^{-1}\right]$
γ	Expansion factor	
η	Efficiency	
ρ	Density	$\left[kgm^{-3}s^{-1}\right]$
α	Velocity of sound	$\left[msec^{-1}\right]$

Subscripts and superscripts

Abbreviation	Meaning
x	pressure ratio factor
Z	Compressibility factor
G	Mass flux
B	Sizing constant
F_p	Piping geometry factor
F_p	Piping geometry factor
G_g	Specific gravity at standard conditions relative to air
P_r	Prandtl number
N_u	Nusselt number

Contents

1 Introduction

As an aircraft flies with varying longitude, latitude and altitude throughout an operation, atmospheric conditions change rapidly which results in inconsistent temperature and pressure inside the cabin. Such inconsistencies in atmospheric parameters bring challenges to survival limitation of human beings.

In order to correct the atmospheric parameters to the accepted physiology flight safety level. To cope with moisture precipitates of bleed air flow at various altitude to provide optimum humidity by ensuring the air in the aircraft always contains sufficient concentration of oxygen[1]. As well as, to maintain safety level limitation that does not exceed to the determined material properties of internal structure of an aircraft; the special system within the aircraft commonly termed as environmental control system (ECS) that comprise air conditioning system and pneumatic system is engineered to regulate the air for cooling, heating, ventilating and pressurizing the flight crew, passenger and cargo compartments.

Compared to past, aircraft performance has remarkably improved and at the same time operation levels has increased which has attributed to more difficult conditions inside the cabin. Generally, kinetic heating, solar heating, avionics heat loads and airframe system heat loads are the major sources of problems that encourage scrutiny on various systems within aircraft. While at higher altitude, the temperature decreases beyond the limitation of human survival, on the other hand, bleed air temperature can be high up to 180-400 Celsius degrees which have to be regulated within each component before it enters the cabin to create a comfortable environment.

These complex phenomena that change with atmospheric parameters within the system and physical restrictions hold by each component have to be covered during the design of the ECS. That includes the rate of processes involved with mass flow, heat transfer, work transfer, steady flow, turbulent flow, energy conversion cycles and most importantly the behavior and response of ECS components while ram air and bleed air passes through it.

Generally, initial design procedure of the ECS is examined by integrating thermodynamic cycle of each component within the ECS system to generalize a synthesis of calculated theoretical results, which is an iterative process. This approach can capture major aspects of thermodynamic process and behavior but widely surpass the cost and limits the meaning of time. Due to this, Simulation-Based Engineering (SBE), which represents an extension of theoretical science based on mathematical equations to characterize physical properties of components or consequences of scientific theories in digital form are more preferred [2].

SBE models primarily focus on computational tools to evaluate performance parameters which have the ability to visualize the performance of complex systems.

[1] As altitude increases, the total quantity of all the atmospheric gases reduces rapidly. However, the relative proportions of nitrogen and oxygen remain unchanged up to about 50 miles above the surface of the earth. The percentage of carbon dioxide is fairly stable. The amount of water vapor and ozone vary[1]

This gives an alternative to experimental prototype testing when phenomena within systems are not observable, time-consuming or expensive for the experimental tests.

With an approach of SBE, the primary focus of this project is to develop a generic model of an ECS in Modelica and Dymola by utilizing already developed virtual digital components[2] library for the ECS modeling developed by the Institute of Thermo-Fluid Dynamics at Hamburg University. During this procedure of development, analysis of the various design of ECS is generalized which are discussed in later chapter two. At the same time, the design of system model and simulation in dymola is performed for each component to verify with the corresponding theoretical formulas in MATLAB which are discussed in detail in chapter four.

After a successful simulation of the ECS model, it can enable and simplify the design procedure. This can be very helpful to predict cabin conditions especially to improve the system efficiency with minimal cost or to determine problems and issues before developing a prototype.

1.1 Scope

As stated above, the atmospheric parameters are unpredictable variable and difficult to detail the behavioral properties with a result of countable instantaneous experimental or observable ordered data. Daniel Perez Linares[3] mentions in his thesis report that no in house ECS model is available to predict cabin conditions for every flight case as atmospheric parameters are never the same. However, prediction can be made by gathering data for components parameter of ECS such as efficiency, mass flow rate under various angles of attack, temperature and pressure ratio of each component and other necessary values of the atmospheric parameter from several flights under various ambient conditions. With the help of collected data, it is possible to reflect the change of properties in the desired environment and visualize the variation in ECS parameters by making an appropriate model in available software to reflect the real system by simulating it.

With the advancement in computer technology and mathematical capability with respect to time, it is now possible to develop components that are slotted within ECS. These virtual components can define the properties of physical components for further studies. These concepts are mimic in several forms, which can be written in an existing programming language such as, Modelica language, C languages, Java, Python, Eiffel, Lexico e.t.c. Once theoretical relation between components is established, a system can be developed which can further mimic the change in ECS for the desired environment by simulating it.

Based on the C language incorporated with an approach of equation-based programming, which forms a Modelica language is one of the promising language used for developing components to model complex physical system. After the development of components, software as Open Modelica, Modelica, Dymola is used for GUI simulation enviornment. Even though there are several proprietary and commercial

[2]Vitrual Digital prototype components, a mathematical equation based components that can mimic most of the properties of the real component used in system that can be developed in commercial or free open source software such as, Open Modellica, ch, GCC, FORTRAN e.t.c

libraries dedicated and tailored for the ECS - only few are publicly available or as open source libraries. Among few, **Philip Jordan** and **Gerhard Schmitz** [4] work on developing TTECCS library5.2 in Modelica language by using comparative theoretical analysis has paved the new way towards developing ECS. This has shown an optimistic bigger picture for simulation by enabling an efficient model integration of an ECS, that can be easily updated, reintegrated, and reiterated according to the availability of new information.

1.2 Aim and Objectives

To further carry out the project, TTECCS library is analyzed to identify components to be used in the ECS before verifying with theoretical formula. This concept is further quantified with specifications of the configuration, constraint in the system, and criteria for a generic ECS system. Which then follows an analysis to determine the ability to simulate the overall temperature and pressure for specific condition by giving inlet mass flow rate, pressure and temperature for each component and subsequently to overall ECS of an aircraft.

To achieve results as mention in the preceding paragraph, each component developed by Philip Jordan and Gerhard Schmitz[4] is verified against the theoretical formulas and simulated results are validated based on the available data.

Throughout the overall simulation, pressure drop, temperature drop in the pipeline and energy loss in compressor, turbine, heat exchanger occurs. Change in energy and pressure, temperature, and other associated variables are estimated with the theoretical formula to control the simulation in each pipe, heat exchanger, condenser, water extractor, compressor, and turbine. Once each component required data are calculated overall simulation is performed to achieve the preferred condition inside the cabin.

Therefore, the final goal is to identify the suitable components from TTECCS library to develop generic ECS and implement it in a Modelica to provide a successful simulation with precise results.

1.3 Work Procedure

After a general understanding of the ECS system, conceptual design of the initial layout is designed based on the literature review of the ECS in existing aircraft. This is followed by a detailed evaluation and comparison of various ECS, that can appropriately characterize generic ECS. During this procedure, first phase begun with literature review[5],[6],[7],[8],[9],[10],[11],[12] to essentially comprehend the physics and progress in ECS that happened with respect to time. Correspondingly, the principle behind the Modelica language is studied.

Following the literature review, a simulation tool for the ECS development is understood, which is followed by verifying selected components from TTECCS to the theoretical formula results obtain in MATLAB. Once the components are verified from TTECCS library, simulations are performed. During the simulation, parameters that impact mass flow rate, pressure, temperature were noted for further necessary calculation. Simultaneously generic ECS layout is sketched. Detail approach followed for system design is mentioned in section 4.2. Then, with an iterative procedure final simulation is performed. In the last phase, post -processing is done, data extraction from simulations was carried out and compared with theoretical formula results for final analysis. The chart in figure 1 shortly depicts the methodology followed to carry out the work.

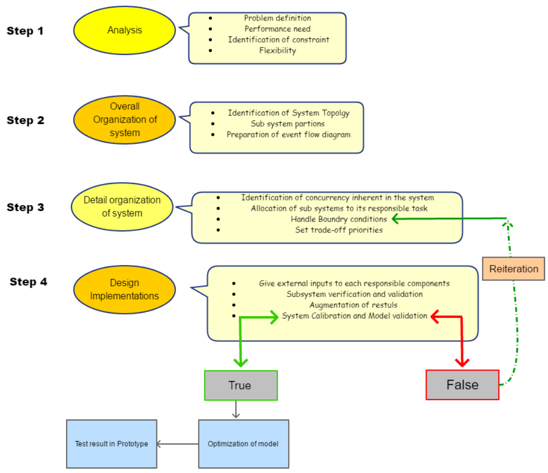

Figure 1: Methodology followed to carry out this work

1.4 Assumptions, Limitations and Delimitation

Most realistic ECS experimental and research results are highly confidential and not available to the general public. In this thesis work, assumptions are made according to the operation and function of the component that exists more in a theoretical framework. Major assumptions, limitation, delimitation includes:-

- In high temperature, the interaction between molecules of real gases is very fast and the volume of molecules are considered as insignificant. Thus, Bleed air is assumed as an ideal gas.
- No moisture precipitates in air(*Medium*) is assumed.
- Smooth Aluminum is considered as a material of pipe to calculate the skin friction.
- Geometrical values of pipes, heat exchangers, fins are approximated as realistic as possible; however, the values are not tuned to any specific aircraft.
- The efficiency of components are estimated by correlating temperature behavior of Airbus A320 within each component.

- The free TTECCS library is used to develop an ECS. Utilities and functions files such as *(LTSmedia.ht, Fluid.dll e.t.c)* that correlates dynamic fluid properties were not provided which limited to only use of dry air as a medium during the simulation.

- Free TTECCS components library do not support reversal flow condition due to which flow is considered as non reversible in each components.

- Base class files such as (*LTSmaps.h, LTSmaps.lib, LTSmaps.dll e.t.c*) in the library are missing, which further limited the use of components based on performance data.

- Exact ECS architecture that correspond to the real ECS in aircraft were not available. Due to this, only simplified version of the ECS that resembles the configuration of the existing aircraft is developed within this thesis work.

- Due to time constraint, only three different types of simplified the ECS architecture are illustrated in this work.

- Inlet pressure at the source (Bleed air) was defined and investigated only under certain ranges and circumstances. Thus, results obtained here may limit the generality of situation and circumstances to other people.

2 The ECS

Although technology for ECS system has advanced with different new types of components with varying architecture, the basic working principle for ECS remain almost same. In general, air is compressed to high pressure and temperature which is further conditioned in Environmental Control Unit (ECU) also called Air Condition System (ACS), where moisture is controlled and temperature necessary for heating and cooling is established. Then the conditioned air is delivered to the cabin to maintain a comfortable environment.

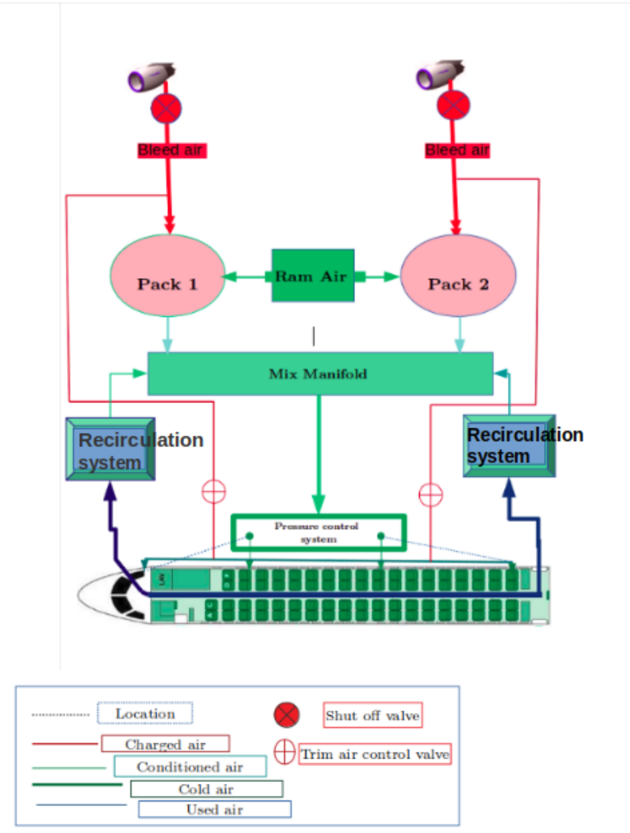

Figure 2: Schematic of Basic configuration of Environmental Control System

2.1 Bleed Air System

Air is bled from one or two compressors from the engine, as shown in figure 2. Generally, air is bled from an intermediate or high-pressure stage of the compressor depending upon the engine power setting[13]. At lower power setting the air is extracted from the high-pressure section of the compressor while at higher power setting air is extracted from the intermediate or lower stage of the compressors[5]. Even though the air tapped from the engine at the high-pressure stage of the compressor has high pressure and temperature than required, tapping air from the lower compressor stage can be detrimental to engine performance[14].Therefore, bleed air can be tapped according to the engine power setting, which can vary upon engine types and their characteristics.

This tapped (bleed) air flows through air pressure and regulation valve. The downstream pressure is regulated by the High-pressure valve (HPV) and pressure reduction valve (PRV). It is regulated to a constant value approximately 40-65 psi[15], that is, it does not correspond and monitor to upstream[3] pressure before entering to pre-cooler which is further ducted through the wing. In most existing commercial aircraft, after the bleed air pressure is reduced to a required value, temperature and mass flow of bleed air is regulated by the flow control valve (FCV)[16] before entering the Air conditioning unit(ACU/ECU).

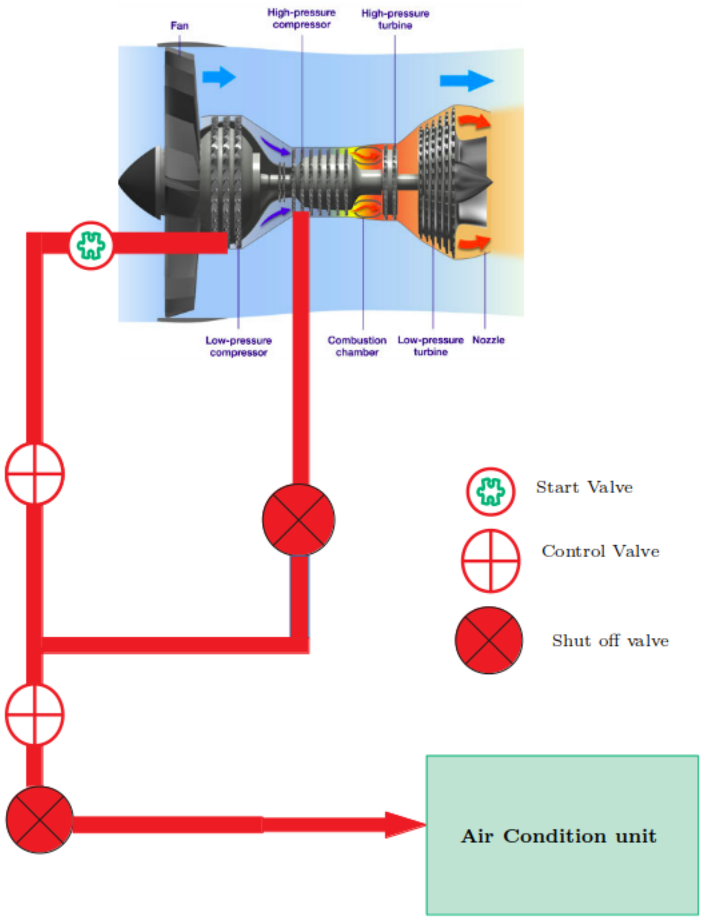

Figure 3: Schematic of Basic Configuration of Bleed air system

[Note: In the figure *control valve* represents *pressure regulation* and *massflow* rate control valve]

[3]Downstream, Here it refers to flow after passing the valve. Upstream, Flow before passing the valve

2.2 Ram Air System

In this system, the atmospheric air is used to cool the bleed air with an intermediate refrigeration component heat exchanger by scooping air within it and then moving downstream as shown in figure 4.

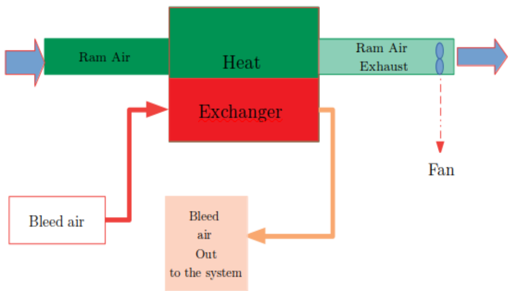

Figure 4: Schematic of Basic Configuration of Ram air system

2.3 Wing/Engine Anti-ice System

This system is installed within part of ECS in the aircraft in order to prevent effects of icing at the wing leading edges and engine intakes. The schematic of the wing anti-icing system is shown in figure 5.
In order to melt the formation of ice in the wing and at the engine, the source of heat (engine bleed air) is routed such that it passes through it. The flow of hot air to the outer wing leading edges is controlled by the wing anti-ice valve (WAV). After the WAV, air is passed down to the leading-edge heating duct. This duct is usually in a shape of the pipe, consist of holes to allow a flow of air on to the inner surface to of the leading edge where the pressure of air in the ducting is controlled to 20-25 psi[5].

Telescopic ducting is utilized where the ducting moves from fixed wing to movable slat structure and flexible couplings are used between the adjacent slat sections. These devices accommodate the movement of the slats sections relative to the main wing structure as the slats are activated. The air is bled out into the leading-edge slat section to heat the structure before dumped overboard. A pressure switch and an overheat switch protect the ducting downstream of the wing anti-ice valve from overpressure and over temperature conditions. Engine anti-icing is similarly achieved.

2.4 Air Conditioning System

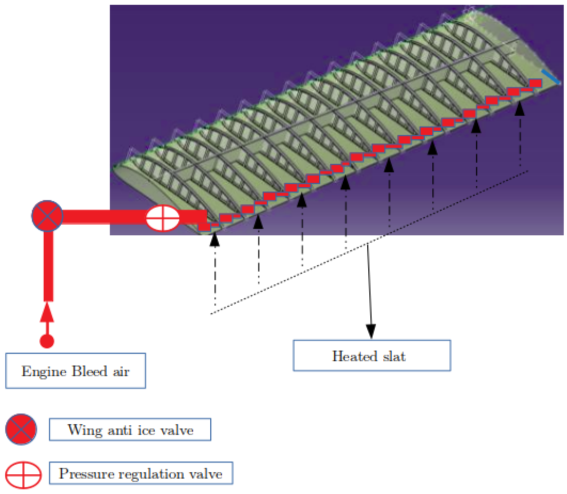

Figure 5: Schematic of Basic Wing Anti-ice System

The air conditioning system is typically made up of an air conditioning pack, the recirculation system and air distribution system to control the interior environment of an aircraft. The primary function of the air condition system for commercial aircraft includes:

- To generate conditioned air flow for air pressurization and ventilation
- To control the flight crew and passenger compartment cabin temperature
- Recirculate the airflow around the cabin for ventilation[4] purposes
- Flush unpleasant air from the lavatories and galley

Mainly there are two types of aircraft condition systems that are used on aircraft :

1. Air cycle air condition system
2. Vapor cycle air conditioning system

2.4.1 Air cycle air condition system

These systems are popular in most of the turbine powered aircraft[5]. Such systems make use of engine bleed air or APU pneumatic air during the conditioning process. This system undertakes process by first cooling high pressurized bleed air down to a required temperature in the heat exchanger using ram air as a coolant. The air is then expanded in the turbine to reduce the temperature and pressure further. Even though there are different types of air cycle air condition system the

[4]Ventilation is usually an open cycle, with used air being dumped overboard. Sometimes the used air is first routed through equipment compartments to condition them. If the recirculation system is being used than ventilation becomes closed cycle loop.

basic principles are almost similar as stated above. The different type of Air Cycle air condition system includes:

1. **Turbofan system**: Generally used in low-speed civil aircraft in which the fan provides the load for the *expansion turbine*, it is usually large in size from where the total cooling ram air passes. As the pressure drops, corresponding temperature drops. Figure 6 depicts the basic configuration of turbofan system [5].

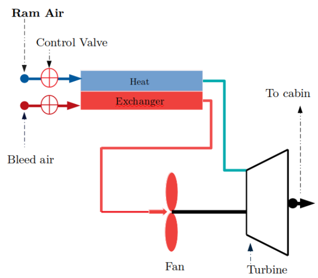

Figure 6: Schematic of Basic Turbofan System

2. **Bootstrap system**: Also known as Turbo-Compressor system, these systems are generally used in high ram temperature conditions which consist of cold air unit and heat exchanger. Charged air passes through a compressor and a turbine but a heat exchanger is interposed between these two units so that the compressor is situated upstream of a heat exchanger. A compressor and a turbine are mounted on the same shaft and a turbine drives the compressor. A compressor is used to increase the pressure and temperature. After, it passes to a heat exchanger where the temperature is lowered by the use of ram air.

   Due to rapid quenching of charged air, it may cause the condensation when the aircraft is operated in humid air. Due to this, a water extractor is added on the turbine inlet to remove the water droplets. Mostly in cold nights, as the air expands across the turbine temperature may drop below zero-degree. Because of this, additional cold air unit bypass line is added which is used to vary the turbine outlet temperature as per the required value in the cabin. The generic schematic of the Bootstrap system is shown below in figure 7.

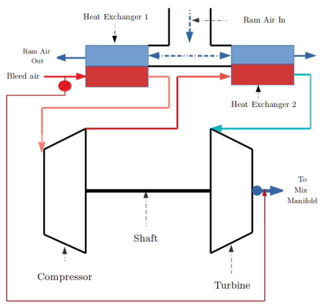

Figure 7: Schematic of Basic Configuration of the BootStrap system

3. **Reversed bootstrap system**: As the name suggests, in this type of system, the charged air passes through the turbine before the compressor. Following the ram air cooling in the primary heat exchanger, air is further cooled in the regenerative heat exchanger and then further expanded in the turbine to achieve required cabin pressure and temperature. This air further passes to the coolant side of the regenerative heat exchanger before being compressed by the compressor and dumped overboard[5].

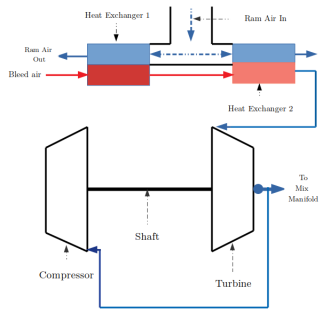

Figure 8: Schematic of Basic Reverse bootstrap system

2.4.2 Vapor cycle air conditioning system

These systems are most popular in reciprocating aircraft, which is a closed loop system, where, the heat load is absorbed by the evaporation of a liquid refrigerant such as freon in an evaporator[5]. The main working principle of the vapor cycle air condition system includes compression of the refrigerant in the compressor before heat is rejected by the refrigerant in the condenser towards a heat sink. And then, the refrigerant flows back to the evaporator via expansion valve where heat is absorbed by the refrigerant[17].

2.4.3 System Operations of Air cycle air condition system

1. **Air condition packs**: The need for bleed air and ram air is based on the principle of aircraft performance according to the elevation aircraft is flying. This includes several aircraft performance parameters such as Angle of Attack, Mach number, Drag etc.

   To establish overall purpose in the utilization of the bleed air and ram air such that, there is always access to sufficient mass flow of bleed air and to ensure it does not surpass more than the requirement; distinct interacting component within ECS are combined to make a system. Common components include *Flow control valve, Trim air Valve, Primary heat exchanger, Main heat exchanger, Compressor, Turbine, Fan, Condenser, Water extractor, Plenum* etc.

These embedded interconnected components within the ECS system continuously works to maintain appropriate flow rate, temperature, pressure, essentially dry, sterile and dust free conditioned air as per requirement before delivering to the mix manifold is termed as Air conditioning pack. The schematic of the air conditioning pack is shown in figure 9.

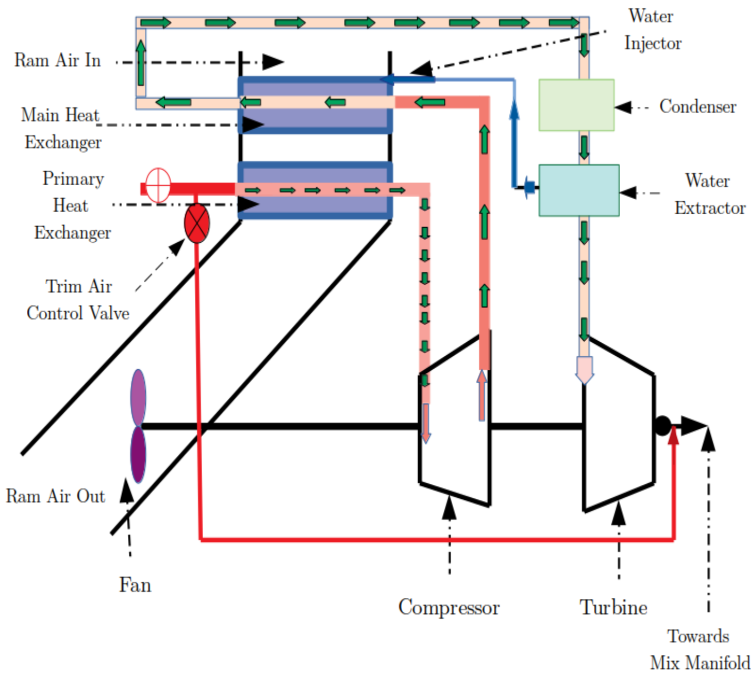

Figure 9: Schematic of Generic Air condition pack based on bootstrap system

2. **Recirculation system**: The concept of reusing the dumped cabin air by filtering and using it again by mixing with the airflow from the engine is classified as a recirculation system. This system is typically made up of an air filter or a recirculation filter and a recirculation fan. The primary objective of a recirculation system is to reduce bleed air demand, therefore, fuel burn. Recirculation system also promotes more evenly distribute air throughout the cabin that minimizes the need for stratification and excessive temperature variation zone within it. Additionally, this system increases the efficiency of cabin air extraction thus circulation of air within the cabin. The schematic of the recirculation system is shown in figure 10.

3. **Mix manifold**: The volume of air passed through air conditioning packs is monitor and combined with an almost equal (or can vary in ratio of 40-60) quantity of filtered recirculated air from the cabin. This chamber where mixing is done is the mix manifold.

4. **Air distribution system**: The distribution of the supplied air from the mix manifold according to the arrangement of the cabin zone is done by the air distribution system. Normally, the ducts of the distribution system are installed below the floor and overhead compartments of the seat arrangement.

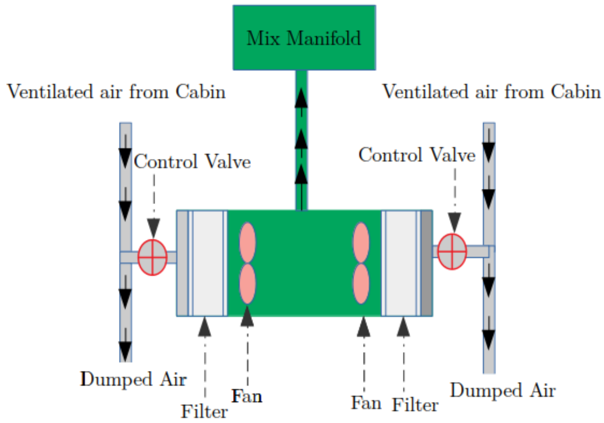

Figure 10: Schematic of Recirculation system

In need, trimmed air is added to match the required supply of air per seating zone, which is in most cases between 10- 20 degree Celsius. The outlet of the duct are carefully designed such that air leaves with a velocity at 152.4 meter per minute[18] by creating a circular airflow pattern. Also, air velocity have to generate the sufficient momentum to sweep the cabin wall and cabin floor to wash out any cold pockets of air within the cabin for a comfortable environment. The air volume is then circulated within the cabin while continuously mixing with cabin air for 2 to 3 minutes before it is all exhausted through the returned air grilles[18]. The exhaust air in the aft section is continuously extracted by the cabin pressure outflow valve, while in the forward section it is extracted from beneath the cabin floor by recirculation fans before processing to the recirculation filter. In some aircraft, recirculated air is also used for avionics cooling.

5. **Cabin pressure control system**: This system monitors the airplane flight mode, altitude, cruise, climb or descent modes at various altitude to further allow air to escape continuously from the cabin by opening or closing the cabin pressure outflow valve, which is normally located in the lower aft of the fuselage. The outflow valve continuously maintains cabin pressure as close to the sea level without exceeding a cabin to the outside pressure differential of 8.60 psi[18]. This valve also controls the airflow to escape according to the aircraft altitude. In general, normal pressure change rate are 0.26 psi[18] per minute during ascending and 0.16 psi[18] while descending for commercial aircraft. Normally, there are two type of pressure outflow valve which are categorized as a positive or negative pressure valve that opens according to the differential pressure between the outside and inside cabin[7].

2.5 Types of ECS

The architecture and stratification of the component within the ECS are based on operating condition, which differs according to the characteristics of the aircraft.

The overall ECS are primarily categorized into two types as open cycle and closed cycle. In addition to these two types of ECS, with the introduction of no bleed air system architecture in the Boeing 787 has further introduced a new type of ECS, which may be referred to the third type of ECS system. However, the operating principle still falls within the open loop or closed loop configuration.

1. **Open Loop**: ECS that continually bleed air from the engine and refrigerates the air by air condition system and dumps the air overboard after use from the cabin are called open loop ECS.

2. **Closed Loop**: ECS system that reuses the air after being used in the cabin by filtering in the recirculation system before passing the air to mix manifold, such arrangement within ECS are closed loop system.

3. **Electric ECS**: With reference to Boeing director Mike Sinnett [19], in this system it emphasis on electrical systems by incorporating the concept of no-bleed air. This replaces most of the pneumatic systems and mix manifold and converts the power source of most functions formerly powered by bleed air to electric power.

3 Component Identification And Conceptual Layout of ECS

This chapter provides information on the mathematical background of the component that will be used in final ECS layout. In order to visualize the behavior, comprehensive assessment of each component based on the mathematical equation that characterize properties and define domain are analyzed, which are then solved in MATLAB. During this procedure, estimation of uncertainties in each component is assessed based on parametric uncertainties that were taken from the past research experiment papers which are noted as it is excerpted.

3.1 Component Identification

1. **Pipes/Ducts**: Here, pipe/ducts represents the physical volume occupied by the air particles within the circular cylindrical form. Gases enclosed within a pipe travels with a certain speed due to energy or pressure difference causing the flow to move. Therefore, the pressure reduces significantly and energy losses occur due to friction or internal turbulent phenomena of air molecules. If the operating conditions differ from design condition due to overestimation or underestimation of the system losses, the whole system may fail. Due to this, it is required to estimate the temperature drop and pressure loss within the pipes appropriately.

   Governing equations for non-branching, steady flow in pipes are derived from the fundamental principles of the conservation of mass, energy and momentum[20]. In addition, the equation of state that relates gas intensive properties, as well as the second law of thermodynamics is used.

   From conservation laws, the continuity equation for compressible flow is given by,

$$\dot{m} = \rho_1 * A_1 * U_1 = \rho_2 * A_2 * U_2 = constant \tag{1}$$

   where,

   Subscript 1 refers to the inlet and 2 to the outlet
   $\dot{m}$, Mass flow rate
   ρ_1, Fluid Density
   A_1, Cross sectional
   ρ_2, Fluid density
   A_2, Cross sectional area
   U_2, Mean velocity of the flow

The Reynold number of the pipe is given by,

$$Re = (\dot{m} * d)/(A * \mu) \tag{2}$$

where,
$\dot{m}$, Mass flow rate
d, Pipe Diameter
A, Cross sectional Area
μ, Absolute Dynamics Viscosity

Velocity of the sound is given by,

$$\alpha = (\gamma * R * T)^{0.5} \tag{3}$$

Where,
α, velocity of the sound
γ, Specific heat ratio
R, Gas Constant
T, Temperature

The Mach number is given by,

$$M = U/\alpha \tag{4}$$

Substituting

$$U = \dot{m}/A$$

in equation 4 gives,

$$M = \frac{\dot{m}}{A * \alpha} \tag{5}$$

where,
M, Mach Number
U, Mean velocity
α, Velocity of the sound

Step to calculate the pressure drop along the pipe for low compressible flow are as follows:

(a) Define the geometric parameters of the pipe: the Diameter and the length.
(b) Define the flow parameters, mean velocity and Reynolds number which can be calculated from the above equation 1,2,3,4. Calculate the Hydraulic Diameter of the pipe,

$$D = 4 * \frac{A}{W_p} \tag{6}$$

where,
D, Hydraulic Diameter of the pipe
A, Cross sectional area of the pipe
Wp, Wettted perimeter of the pipe

(c) Assume roughness value k, according to the materials used in the pipe. Here, a smooth pipe of aluminium is considered and value is excerpted from [20] Table 8.1.

(d) Calculate the friction coffecient for smooth pipe f, which is given by colebrook-white equation [20]

$$f = \frac{0.25}{\left[log\left\{\frac{k}{(3.7*D)} + \frac{5.74}{Re^{0.9}}\right\}\right]^2} \tag{7}$$

(e) Calculate the system loss coffecient k, which is given by

$$K = f * \frac{L}{D} \tag{8}$$

where,
L,Length of the pipe
D, Hydraulic Diameter of the pipe

(f) calcualte the pressure drop along the pipe ΔP, given by,

$$\Delta P = K * \rho * U^2/2 \tag{9}$$

where,
U, Mean Velocity
ρ, Density of the air according to the temperature

2. **Heat exchanger**: A heat exchanger is a heat transfer mechanical component that is used to transfer the internal thermal energy between two or more fluids at different temperatures. Mostly, heat exchangers are made up of the heat exchanging elements such as a core or matrix containing heat transfer surface and fluid distribution elements such as pipes, gasket, fin, fixed matrix e.t.c.[21].

   Principally, there are various configuration of heat exchangers which are classified according to the construction, heat transfer process, the degree of surface compactness, flow arrangements, pass arrangements and phase of the process fluid. The selection of a heat exchanger is usually established by identifying the service requirement and emphasizing the requirement of usage. In this thesis work, cross flow tube-fin heat exchanger is selected based on the work of Xiong peng [7] . Thus, cross flow tube fin theoretical properties are modeled in MATLAB. Although heat exchangers may differ structurally according to the configuration, the fundamental thermodynamic principle remains the same. To develop the relationship between the heat transfer rate (q), the surface area (A), fluid terminal temperature T, and flow rate ($\dot{Q}$), the energy conservation, and heat transfer rate equation are utilized.

The energy conservation equation for a heat exchanger having an arbitrary flow arrangement is given by [21]

$$q = C_h(t_{h,i} - t_{h,o}) = C_c(t_{c,o} - t_{c,i}) \tag{10}$$

The first law of the thermodynamics for any two fluid is given by [21]

$$m_h * C_h(t_{h,i} - t_{h,o}) = m_c * C_c(t_{c,o} - t_{c,i}), \tag{11}$$

And the heat transfer rate is given by,

$$q = h_h * A * \Delta T \tag{12}$$

Where,
$t_{c,i}, t_{c,o}$ are cold fluid terminal temperature (inlet and outlet respectively)
$t_{h,i}, t_{h,o}$ are hot fluid terminal temperature(Inlet and outlet respectively)
C_c is the capacity rate of the cold fluid, heat transfer coffecient
C_h is the capacity rate of the hot fluid, heat transfer coffecient
ΔT is the true mean temperature difference
m_h, m_c are the mass flow rate of hot side and cold side respectively
h_h, A is thermal conductivity and overall Area

The steps to calculate the tempearture drop and pressure drop in a heat exchanger are as follow:

(a) State the mass flow rate
(b) Calculate the hydraulic diameter of the pipe from above
(c) Calculate the density of the air flow, the pressure of the bleed air in the inlet of a heat exchanger has to be considered, which is approximately 3700 kPa [5]
(d) Calculate the dynamic viscosity, which is determined by the airflow temperature and expressed by sutherland formula

$$\mu = \mu_{ref} * (T_{ref})^{1.5} * \left[\frac{(T_{ref} + S)}{(T + S)} \right] \tag{13}$$

where,
$\mu_r ef$, Dynamic viscoisty of an air in standard temperature
S, Sutherland Temperature $[K]$
T_{ref}, Standard Atmospheric condition temperature
T, Temperature of the air

(e) Calculate the Mean velocity of hot flow from above equation 4.
(f) Calculate the Reynold number from above equation 2.
(g) Calculate the thermal conductivity of the fluid in the hot side of heat exchanger K_{air}[7].

$$K_{air} = T_{bleed}^3 * (1.52 * 10^{-11}) - T_{bleed}^2 * (4.86 * 10^{-8}) + T_{bleed} * (1.02 * 10^-4) - 3.93 * 10^{-4} \tag{14}$$

(h) Calculate the Prandtl number according to

$$p_r = \frac{(\mu * C_p)}{K_{air}} \tag{15}$$

where,
C_p, Specific heat of air at constant temperature [7]

(i) Calculate the Nusselt number [22]

$$N_u = \left[\frac{(\frac{f}{8}) * (Re - 1000) * P_r}{1 + \left\{ 12.7 * \left(\frac{f}{8}\right)^{1/2} * (P_r^{2/3} - 1) \right\}} \right] \tag{16}$$

(j) Calculate the heat transfer coffecient h according to [22]

$$h = \frac{(N_u) * K_{air}}{D_h} \qquad Unit \left[\frac{W}{m^2}K\right] \tag{17}$$

(k) Calculate the total heat transfer area at hot side and cold side [7]

$$A_{hs} = 2 * N_t * l_b * l_c * \left[\frac{(s_f - T_{hf}) + (2 * fin_h)}{S_f}\right] \tag{18}$$

where, N_t,Number of the tube passes
fin_h, Fin height in [m]
$T_{h,f}$, Fin thickness
L_a, l_b, L_C, Length breadth and height in [m] respectively

$$A_{cs}, 2 * N_t * l_a * l_b * \left[\frac{(s_f - T_{hf}) + (2 * fin_h)}{S_f}\right] \tag{19}$$

(l) Calculate the total surface temperature effeciveness of fin [23]

$$E_{ft} = 1 - [(1 - \eta_{fin}) * (\frac{A_{hs}}{A_{cs})}] \tag{20}$$

where,
E_{ft}, Effeciveness of the fin

(m) Calculate the Overall thermal resistane R_{TR} [21]

$$R_{TR} = \frac{1}{\eta * ha} + \frac{1}{(A_{cs}/volume_{hs})/(A_{hs}/Volume_{hs})} * h + \frac{T_{hf}}{K_{fin}} \tag{21}$$

where,
A_{hs}, Area of the hot side
A_{hs}, Area of the cold side
$Volume_{hs}$, volume of the heat exchanger
K_{fin}, Thermal Conductivity of the fin

(n) Calculate the overall heat transfer coffecient U_a[23]

$$U_a = \frac{1}{R_{TR}} \tag{22}$$

(o) Repeat all the step from $[a - n]$ for cold side

(p) Calcualate the heat capacity rate for both hot side and cold side [Ca_{max}]

$$Ca_{max} = m * C_p \tag{23}$$

where,
m, mass flow rate
C_p, Specific heat of air at standard atmospheric pressure

(q) Calculate the stream heat capacity ratio

$$C_{aR} = \left(\frac{C_{a_{max}}}{C_{a_{min}}}\right) \tag{24}$$

where,
$C_{a_{max}}$, Maximum heat capacity rate, that can be either from hot side or cold side which is determined from equation 23

(r) Calculate the number of transfer units

$$NTU = \frac{U_a * A_{cs}}{C_{a_{min}}} \tag{25}$$

(s) Calcualte the effectiveness of the heat exchanger which is given by by,[23]

$$E_e = 1 - exp\left[\frac{(exp(-C_{aR} * NTU^{0.78}) - 1}{C_{aR} * NTU^{-0.22}}\right] \tag{26}$$

(t) Calculate the total heat transfer rate [Q][23]

$$Q = E_e * C_{a_{min}} * T_{bleed} - T_{Ram} \tag{27}$$

(u) The outlet temperature for the hot side of Heat exchanger is given by,

$$T_{phx} = T_{bleed} - \left(\frac{Q}{C_{a_{min}}}\right) \tag{28}$$

(v) Tube length per pass is calcualted by[22],

$$L_{tube} = \frac{(NTU * C_{a_{max}})}{U_a * N * 2 * \pi} \tag{29}$$

(w) Pressure drop in the Heat exchanger

$$\Delta P = \frac{*L_{tube} * \rho * U^2}{2 * D} \tag{30}$$

where,
D, Hydraulic diameter which can be calculated from equation 6

(x) Outlet pressure from Heat exchanger for hot side

$$Pressure_{outlet} = Pressure_{Inlet} - \Delta p \tag{31}$$

(y) Similarly the outlet Temperature and pressure drop can be found for the Ram air flow by following the above steps from p to w

3. **Control Valves** : Control valve are the variable resistance device that controls the flow rate, pressure, temperature by deliberately introducing a pressure drop in the system. Generally, control valve consists of two parts: An actuator which translates the ouput signal of the controlling device into an action involving large force or the manipulation of the large power and device responsive to the actuator force which adjusts the value of the manipulated variable. Examples of the flow control valves includes selector valves, check valves, sequence valves, shuttle valves, quick disconnect valves and hydraulic fuses. Relief valve and shuttle valves are commonly used as pressure control valves in the aircraft[24].

   (a) Check valves: Check valves are automatic valves which open with the forward flow and closes against the reverse flow. It should be designed such that, it operates in and avoids the formation of an excessively high surge pressure as a result of the valve closing. There are several types of check valves such as *Lift check valves*, which uses free moving closure element. *Swing Check valve*, Which uses hinged closure element that is similar to door arrangement. *Butterfly check valve* which closure element is much like a butterfly disk that has two pivot points located on each side. *Diaphgram check valve*, which uses a preformed elastomeric closure element that opens with upstream flow and returns to its performed closed shape with reverse flow.[25].
   Check valves are designed by comparing the required closing speed with the closing characteristics of the valve . For basic body sizing of the gas service control valves, depending upon the given services condition or variables, one of the four equations below are used.[25]

$$w = 63.3 * F_p * C_v * \gamma * \sqrt{x * P_1 * \gamma_1} \tag{32}$$

or

$$w = 19.3 * F_p * C_v * P_1 * \gamma * \sqrt{\frac{x * M_W}{T_1 * Z}} \tag{33}$$

or

$$Q = 1360 * F_p * C_v * p_1 * \gamma * \sqrt{\frac{x}{G_g * T_1 * Z}} \tag{34}$$

or

$$Q = 7320 * F_p * C_v * P_1 * \gamma * \sqrt{\frac{x}{M_w * T * Z}} \tag{35}$$

where,
w , Gas flow rate $[lb/h]$
F_p, Piping geometry factor
$Valve\ sizing\ coffecient$, Valve sizing coefficient
γ, Expansion factor
x, Pressure ratio factor
γ_1, Specific weight at inlet service condtion lb/ft^3
Q, Gas flow $scfh$ (Standard cubic feet per minute)

G_g, Specific gravity or gar relative to air at standard conditions
T_1, Absolute upstream temperature ($°R =° F + 460$)
Z, Compressibility factor
M_w, Molecular weight
P_1, Upstream absolute pressure

Steps for basic sizing of the valve are as follows, All the equation in the following steps are excerpted from Valve Handbook [25]

i. Calculate the pipe geometry factor F_p, Initially it is assumed to be 1.0[25]

ii. Calculate the ratio of specific heat factor f_k

$$F_k = \frac{k}{140} \tag{36}$$

where,
F_k, Ratio of the specific factor
k, Ratio of the specific heat

iii. Calculate the ratio of actual pressure drop to the absolute inlet pressure

$$x = \frac{\Delta P_a}{P_1} \tag{37}$$

where,
x,Ratio of actual pressure drop to absolute inlet pressure
ΔP_a, Actual pressure drop psi
P_1, Upstream pressure at inlet psi

Check if the value of the x is less than $F_k * x_T$[5] Here, x_T is terminal pressure drop ratio which can be determined by various source. Here, appropriate value is excerpted from Table 9.1 of valve Handbok by Philip L.Skousen.[25].

iv. Calculate the expansion factor

$$\gamma = 1 - \frac{x}{3 * F_k * x_T} \tag{38}$$

where,
γ, Expansion factor
If the the flow choked, $(F_k * x_T)$ should be used instead of x in numerator in above equation 38.

v. Calculate the compressibility factor Z
This is determined by calculating the reduced reduced pressure value (P_r) and reduced-temperature value (T_r)

[5]If the value of the x is less than the value of $F_k * x_T$ choked flow is not occurring, if it exceeds choked flow occurs.

where,

$$P_r = P_1/P_c$$

and

$$T_r = T_1/T_c$$

Where, P_1 and T_1 are absolute upstream pressure and temperature respectively.
P_c and T_c are absolute critical pressure and temperature respectively.

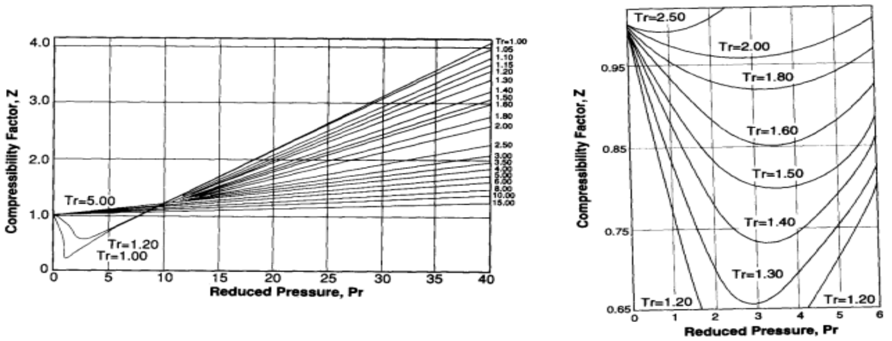

Figure 11: Compressibility factor in relation to reduced pressure, Excerpted from Valve handbook[25] courtesy of Valtek International

vi. calculate the flow-coefficient C_v by using equation from 32 to 34. For these equations initially the pipe geometry factor is assumed to be 1.0 or can be calculated by following the given value in the figure below.

Table 9.5 Piping-Geometry Factors for Valves with Reducers and Increasers on Both Ends*,†

C_v / d^2	d / D				
	0.50	0.60	0.70	0.80	0.90
4	0.99	0.99	1.00	1.00	1.00
6	0.98	0.99	0.99	1.00	1.00
8	0.97	0.98	0.99	0.99	1.00
10	0.96	0.97	0.98	0.99	1.00
12	0.94	0.95	0.97	0.98	1.00
14	0.92	0.94	0.96	0.98	0.99
16	0.90	0.92	0.95	0.97	0.99
18	0.87	0.90	0.94	0.97	0.99
20	0.85	0.89	0.92	0.96	0.99
25	0.79	0.84	0.89	0.94	0.98
30	0.73	0.79	0.85	0.91	0.97
35	0.68	0.74	0.81	0.89	0.96
40	0.63	0.69	0.77	0.86	0.95

*Courtesy of Valtek International.
†*Note:* The maximum effective pressure drop (ΔP choked) may be affected by the use of reducers and increasers. This is especially true of butterfly valves.

Table 9.6 Piping-Geometry Factors for Valves with Reducers and Increasers on Outlet Only*,†

C_v / d^2	d / D				
	0.50	0.60	0.70	0.80	0.90
4	1.00	1.00	1.00	1.00	1.00
6	1.01	1.01	1.01	1.01	1.01
8	1.01	1.02	1.02	1.02	1.01
10	1.02	1.03	1.03	1.03	1.02
12	1.03	1.04	1.04	1.04	1.03
14	1.04	1.05	1.06	1.05	1.04
16	1.06	1.07	1.08	1.07	1.05
18	1.08	1.10	1.11	1.10	1.06
20	1.10	1.12	1.12	1.12	1.08
25	1.17	1.22	1.24	1.22	1.13
30	1.27	1.37	1.42	1.37	1.20
35	1.44	1.65	1.79	1.65	1.32
40	1.75	2.41	3.14	2.41	1.50

*Courtesy of Valtek International.
†*Note:* d = valve port inside diameter in inches; D = internal diameter of the piping in inches.

Figure 12: Piping geometry factor for valves for reduced geometry pressure, Excerpted from Valve handbook[25] courtesy of Valtek International

vii. Approximate the Body - Size, using the manufacturers C_v tables.

viii. Calculate the Mach number ,

$$M_{gas} = \frac{Q_a}{5574 * A_v * \sqrt{\frac{kT}{M_w}}} \tag{39}$$

or

$$M_{gas} = \frac{Q_a}{1036 * A_v \sqrt{\frac{K*T}{G_g}}} \quad (40)$$

where,
M_{gas}, Mach number for gas
Q_a, Actual flow rate [Cubic feet per hour]
A_v, Applicable body flow area
k, Ratio of specific heats
M_w, Molecular weight
G_g, Specific gravity at standard conditions relative to air

(b) Relief valve : Relief valves are self operating valves that are installed in ECS to protect against over pressurization withhin the component, subsequently in the system. When excess line pressure is detected, the pressure relief valve automatically opens and the excess pressure is relieved. Each $Relief\ valve$ has *set pressure*, which is the point where the over pressurization of the system overcomes spring force holding the disk to the nozzle [25].
Basic steps to size the pressure relief valve are as follows,

i. The basic formula for sizing the pressure- relief valve is

$$A = \frac{W}{BKG} \quad (41)$$

where,
A, Flow area pf the pressure relief valve
W, Required mass flow rate
B, Sizing constant
K, Coefficient of discharge
G, Mass flux

ii. Determine if the flow is choked or not choked by

$$\frac{P_2}{P_1} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad (42)$$

where,
P_1, Upstream pressure inlet
P_2, Downstream pressure outlet
k, Isentropic coefficient[6] at operating temperature and pressure

iii. If the flow is nonchoked, The mass flux is given by

$$G = P_1 * \left[\frac{1}{R * T_1 * Z} * \frac{2k}{k-1} * \left\{\left(\frac{P_2}{P_1}\right)^{(\frac{2}{k})} - \left(\frac{P_2}{P_1}\right)^{(\frac{k+1}{k})}\right\}\right]^{0.5} \quad (43)$$

[6] The isentropic coefficient can equal to the ratio for specific heat if the assumption is made that the fluid is pure isentropic flow[25]

Where,
G, mass flux
R, Gas constant
T_1, Temperature inlet
Z, Compressibility factor

iv. Calculate the flow area by

$$A = \frac{W}{BKG} = \frac{W}{BKP_1}\left[\frac{1}{R*T_1*Z}*\frac{2k}{k-1}\left\{\left(\frac{P_2}{P_1}\right)^{2/k} - \left(\frac{P_2}{P_1}\right)^{k+1/k}\right\}\right]^{0.5} \tag{44}$$

where,
A, Flow area
W, mass flow rate
B, 1.0 Metric
K, Cofficient of discharge
Z, compressibility factor[7]

v. If the flow is choked than the inlet pressure is less than critical pressure, In mathematical expression it is given by

$$\frac{P_2}{P_1} < \left(\frac{2}{k+1}\right)^{k/k-1} \tag{45}$$

vi. Calculate the mass flux, if the flow is *choked* it is given by,

$$G = P_1\left[\frac{2}{Z*R*T_1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right]^{0.5} \tag{46}$$

vii. Calculate the flow area, if the flow is *choked* it is given by,

$$A = \frac{W}{BKG} = \frac{W}{BKK_bP_1}\left[\frac{1}{ZRT_1}K\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right]^{0.5} \tag{47}$$

4. **Compressor**: Compressors are the mechanical component that increases the pressure of gas by converting velocity to the pressure. Thus, reducing the volume in a continuous flow. Generally there are two types of compressors: $Axial$ and $centrifugal$. But in the case of an ECS of an aircraft, Centrifugal compressors are used due to their advantages of light weight, simplicity to make in relatively small size, better resistance to foreign object and ability to over a wider range of mass flow rates at a particular speed.
Normally in the procedure of performance and design calculation of centrifugal compressor, each property of each component has to be considered. Such component includes $Impeller$, $Diffuser$, $Half\ vane$, $Scroll$ or $Manifolds$ and their parameters such as $Slip\ factor$, $Pre\ whirl$ e.t.c.. However, to simplify performance calculation hereafter, only ideal state of air, described by its two

[7]This can be determined from step (v) of check valve sizing equation

properties pressure and temperature is taken into consideration.

The velocity triangle in any turbo machine is governed by the relation

$$\vec{C} = \vec{U} + \vec{W} \tag{48}$$

where,
$\vec{C}$, Absolute Velocity
$\vec{U}$, Rotational velocity
$\vec{W}$, Relative velocity

Equation 1 can be written as

$$\dot{m}_1 = \dot{m}_2 \tag{49}$$

Where,
Mass flow rate at inlet $\dot{m}_1$ is given as ,

$$\dot{m}_1 = \rho_1 * C_{a1} * Inlet\ Area = \left[\rho_1 * C_{a1} * \left\{\frac{\pi}{4}\left(D_{1t}^2 - D_{1r}^2\right)\right\}\right] \tag{50}$$

where,
ρ_1,Density at inlet
C_{a1}, Axial velocity at inlet
D_{1t}, Eye root at the inlet
D_{1r}, Tip diameter in the inlet

Mass flow rate at outlet is given by,

$$\dot{m}_2 = \rho_2 * C_{r2} * [b\left(\pi D_2 - nt\right)] \tag{51}$$

where,
ρ_2, Density of the air at outlet
C_{r2}, Radial velocity at the impeller tip
b, Axial width of the impeller
t, Thickness of the blade at the impeller

From Euler Turbo machinery definition, Momentum equation can be written as,

$$\vec{F} = \frac{d}{dt}(m * \vec{C}) \tag{52}$$

Considering steady flow from states 1 to 2, Equation 52 can be written as

$$\vec{F} = \frac{d}{dt}\left(\dot{m} * (\vec{C_2} - \vec{C_1})\right) \tag{53}$$

and the torque force is given by

$$\vec{T} = \vec{r} * \vec{F} \tag{54}$$

Substitution of $\vec{F}$ in equation 54 and 53 gives

$$\vec{T} = \dot{m}(\vec{r_2} * \vec{C_2} - \vec{r_1} * \vec{C_1}) \tag{55}$$

and the vectorial equation 55 in terms of scalar relation becomes

$$T = \dot{m}[(r * C_u)_2 - (r * C_u)_1] \tag{56}$$

where,
(C_{u_2}), Swirl velocity at the outlet
(C_{u_1}), Swirl velocity at the inlet
Assuming the flow enters the impellers axially, there is no swirl velocity at the inlet (C_{u_1})=0, then the equation 56 becomes

$$T = \dot{m}[(r_2 * C_{u2})] \tag{57}$$

Then the power is expressed as,

$$P = T * \omega \tag{58}$$

where,
ω, Rotational speed of shaft
r, radius of the blade
T, Torque
Substitution of equation 57 in equation 58, it becomes

$$P = \dot{m} * r_2 * C_{u_2} * \omega \tag{59}$$

Rotational velocity of air is,

$$U = \omega * r \tag{60}$$

Substitution of equation 60 in equation 59

$$P = \dot{m} * U * C_{u_2} \tag{61}$$

Since, power to drive compressor is greater than the power derived above due to frictional losses and other losses equation 61 becomes,

$$P = \psi * \dot{m} * U * C_{u_2} \tag{62}$$

where,
ψ, Power input factor
From the first law of thermodynamics the net change of energy of fluid is expressed as,

$$\frac{\dot{Q} - \dot{W}}{\dot{m}} = (h_2 - h_1) + \frac{1}{2} * (c_2^2 - c_1^2) + g(z_2 - z_1) \tag{63}$$

where,
h_2, Enthalpy at outlet
h_1, Enthalpy at inlet
$\dot{Q}$, Rate of heat transfer
$\dot{W}$, Rate of work done

Since, potential energy in the compressor is negligible and the flow is assumed as adiabatic flow, heat term is negligible, equation 59 reduce to

$$\frac{\dot{W}}{\dot{m}} = \left(h_2 + \frac{1}{2}C_2^2\right) - \left(h_1 + \frac{1}{2}C_1^2\right) = H_{02} - H_{01} = H_{03} - H_{01} \tag{64}$$

where,
H_{01}, Stagnation Enthalpy at outlet
H_{03}, Stagnation Enthalpy at inlet

From Equation 64, the mechanical input power per unit mass flow rate is equal to the specific enthalpy rise to the compressor, equation 64 reduces to,

$$C_p = (T_{03} - T_{01}) = \psi * C_{U_2} * U_2 \tag{65}$$

From equation 65, the temperature rise in the compressor becomes,

$$\Delta T_0 = \frac{\psi C_{u_2} * U_2}{C_p} \tag{66}$$

where,
C_p, Specific Heat constant

Similarly , isentropic temperature ratio in terms of the pressure ratio of compressor is define as,

$$\pi_c = \frac{T_{03}}{T_{01}} = \left(\frac{P_{03}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} \tag{67}$$

The isentropic efficiency η_c of the compressor is defined as,

$$\eta_c = \frac{\left(\frac{p_{03}}{p_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{T_{03}}{T_{01}}\right) - 1} \tag{68}$$

Then the pressure ratio of compressor in terms of isentropic efficiency is given by,

$$\pi_c = \left(1 + \eta_c \frac{T_{03} - T_{01}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \tag{69}$$

or, from equation 66

$$\pi_c = \left(1 + \eta_c \frac{\psi * C_{U_2} * U_2}{C_p * T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \tag{70}$$

where,
π_c, Pressure ratio

5. **Turbine**: Turbines are the mechanical components that extract energy from the flow and convert it into mechanical or electrical energy. When energy is extracted from the flow the pressure drops and subsequently temperature drops. Similar to compressor, turbine are also classified into two categories as *axial inflow turbines* and *radial inflow turbine* which are similar to centrifugal compressor as both have mixed flow directions. In radial turbines, the flow enters radially and leaves axially close to the axis of rotation. In the case of the ECS, radial flow turbine are used due to their advantages of high reliability, relatively easy to manufacture small scale and high efficiency.

   The design analysis of turbine is similar to that of the compressor which can be derived by the kinematic relation of velocity *equation* 48 and Euler's Equation *equation* 52 and the first law of thermodynamics *equation* 63.

   Total enthalpy drop in the turbine is given by,

$$\Delta T_0 = \dot{m} * C_p * (T_{01} - T_{03}) \tag{71}$$

   where,
   $\dot{m}$, mass flow rate
   C_p, Specific gas constant
   T_{01}, Temperature at inlet
   T_{03}, Temperature at outlet

$$\pi_t = \frac{(P_0)_{turbineinlet}}{(P_0)_{turbineoutlet}} \tag{72}$$

   where,
   P_0, Pressure

   Turbine total to total stage efficiency *(Valid for axial turbine)* is given by the relation

$$\Delta T_0 = \eta * T_{01} \left[1 - \left(\frac{1}{\pi_t} \right)^{\frac{\gamma-1}{\gamma}} \right] \tag{73}$$

3.2 Conceptual Layout of the ECS

After recognition and determination of the purpose of the main components in ECS, it is necessary to establish the desired function of each component such that it delivers the assigned task. The basic task of each component is generalized by relating the components to one another. Thus, forming a system layout of the ECS. Subsequently, the output of the system that is, $Temperature$ and $Pressure$ inside the cabin compartment is analyzed and evaluated. Such that, it is under the qualitative standard requirement set by the Federal Aviation Administration.

This is followed with an approach of an iterative procedure by sketching the layout of a system and acknowledging its alternative so that it can represent and define the concept of generic ECS.

4 Object Oriented Modeling And Interpretation

Object-Oriented Modeling (OOM) is a concept derived from Object-Oriented Programming (OOP), in which different objects (*collection of discrete objects*) describe the system and their relationship to each other. Each object is expressed in terms of characteristics of real-world objects that the system interacts with. Within this interaction, each object integrates function and data according to the orientation of requirement.

The approach to OOM can be refined and classified similar to many other modeling techniques such as functional modeling, procedure-oriented modeling, logic-oriented modeling, constraint oriented modeling, rule-oriented modeling etc,. Common approaches for OOM includes *class-based* (*class orientation*) and *prototype based* and found as a[8] simplified approaches.

The class-based approach is based upon the identification of the properties of an object and their description in terms of a definitional structure [9] called a class[10]. A class describes a group of objects with similar properties (*attributes*), common behavior (*operations*), common relationship to other objects and common semantic purpose. For example, assume the class name *Square* that represent the geometrical figure in XY-Coordinate system. X-Coordinate to denote X-Coordinate of the center which can be 0, Y-Coordinate to denote Y-coordinate of the center which can be 0 and $'D'$ to denote the normal or horizontal distance from the center to each side. Operation of the class *Square* can be calculation of the area of the square by scaling the square (*Sizing method*) with changing the value of D. After assigning the value (*Instantiation*) to D, it exhibits the behavior of class Square. Similarly, with the same assumption of coordinate system, create class *circular Base* in which scaling variables can be named to R to find an area of the circle. And, these two different types of class make the object $Comfort\ Chair$. Portray of object $Comfort\ Chair$ shows that, each object is the result of instantiation of its class and which has own value for each attribute but shares the attribute names and operation with other instances of a class.

In *prototype-based* approach, prototype objects are created by means of copy operation called *cloning*[10]. In each prototype object, it contains a slot consisting of data or method. The concept of cloning is employed by copying existing entities and modifying the copies to produce new entities with similar but not identical properties. Prototypes can be copied and modified to produce new prototypes that can be then cloned to form new objects[10]. For example, in a prototype object named *Dog one*, it contains three slot that contain *Dogcolour*, *Dogweight*, and

[8]This is the subjective claim, and has its limitation due to lack of detail research, reasoning and comparison with other approaches

[9]Here, Definitional structure means that objects with the same *data structure* (attribution) and *behavior* (operations/method) are grouped into class

Dogbehaviour. Similarly, in a prototype object two named *Cat two*, it contains two slots named to *catheight* and *catweight*. And, in third prototype object named *Lion* it contains four slot that contain *lionColour*, *lionheight*, *lionbehaviour* and *lionweight* of lion. Now by cloning method, a new prototype object *Weight of different animal* can be created by copying each animal's weight.

4.1 Characteristics of Object Modeling

An *object model* is the static structure of the system that represents and describes an individual and identifiable item, either real or abstract with a well-defined role in a system or in a problem domain. Each object may consist of a course of events such that it can establish a relationship with other objects attributes and operation [26]. Just as many other models, object model is emphasized as the abstraction of a concept of the system, that identifies the concept of *Classes*, *Attribute*, *Links and associations*, *Generalization and inheritance*, *Multiplicity*, *Aggregation*, *Delegation*, *Ploymorphism* e.t.c. These concepts serve as guidance to define the standardized concept of object-oriented modeling.

1. **Classes**: Classes are the implicit properties of the object that describes a group with similar properties (attributes), common behavior (operations), common relationship to objects and common semantics[27].

2. **Attributes**: Attributes are the data value held by the object in a class. For example *name*, *age*, *weight* are the attributes of *person* object. *Color*, *weight*, *model year* are the attributes of *Car* objects.

3. **Link and Association**: A link is a physical representation that connects the data structure consisting of multiple parts within object instances. For example[10], Joe Smith works for the Simplex company. Here, Joe Smith, *attribute* of the object class is linked with another attribute *company name*. Whereas, a group of link with a common structure and common semantics is called *Association*. For example, *works for company* in the example above is an *association* that associate between two object classes. Therefore, Association represents structural relationship among object and *link* that can be transcribed as an instance of association.

4. **Generalization and Inheritance** : Generalization and Inheritance refer to the concept of abstraction from two or more different classes sharing similarities as well as recognizing and preserving difference within the class. More specifically, *Generalization* is the process of extracting shared characteristics from two or more classes and combine them to form a superclass. Generalization shows that the superclass is an abstraction of sub-classes that inherits from one class to another. The inheriting class is also called descendants (subclass) and the class inherited from is called ancestor (Superclass).

[10]This example is excerpted from chapter 3 subsection 3.2.1 of reference[27]

Inheritance refers to the mechanism of obtaining properties using the generalization structures. For example, From figure 13 below, *Mobile Phone* and *Land Line phone* partially share the same attribute. According to object-oriented modeling perspective, these two classes are similar. During generalization, common attribute are combined to create new superclass *Phone* where *land line phone* and *Mobile phone* become subclasses of the superclass *Phone*. Also, The superclass feature is common that can be passed/inherited to all subclass.

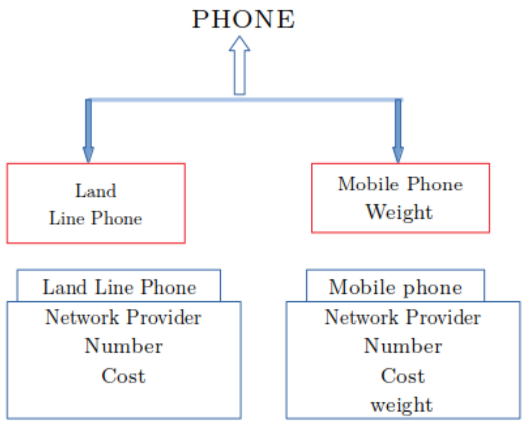

Figure 13: Example of Generalization and Inheritance for phone

5. **Multiplicity**: Generally *multiplicity* specifies how many instances of one class may make a reference to other classes.

6. **Aggregation**: When one object has a relationship to other components and represents the component of the system that is associated with a description of an entire assembly, the concept of *aggregation* is employed. For example, an object name *car* can contain many internal objects as instances such as *wheel*, *seat*, *windows*, *doors* and if it is imagined a *robot* is driving a car. The object *robot* controls and also characterizes the main property of object *car* if the car is being driven. Only in presence of robot, it can be said object *Car* is moving. In this case, if the object *car* is deleted, the object robot still remains the same. This independency to categorize the objects from the entire assembly of the system is referred to aggregation. Therefore, the concept of aggregation does not support reversible relationships.

7. **Composition** : Unlike *Aggregation*, the concept of *Composition* is identified with phrase "*has a*" that express relationship with one or more objects. For example, object *Car* is made up of system that can be represented with object *Electrical System*, *Pneumatic system* and *Sensors*. Each object has each responsibility to deliver to over all system. If any of the objects is deleted main object *car* is nonfunctional.

8. **Delegation** : The concept of delegation is mainly utilized in the *prototype based* approach where class does not exist and the idea of inheritance is not supported. Delegation employs the idea of using data from one slot/object to another object explicitly in case of requirement. For example, object $P1$ contains two slots $S1$ and $S2$. S1 contains data of x and y in a two-dimensional coordinate system with (0,0) as the origin. Slot $S2$ contains the formula (*method*) to calculate the area of the circle. Another object $P2$ has one slot that has properties to scale the *Diameter* of the circle. In such a case, if the area of the circle has to be calculated according to the scaled *Diameter* from object $P2$, the method to calculate the area can be directly passed to object $P2$ from object $P1$. This concept of passing a message from the transmitting object to the receiving object is termed as delegation. In this example, slots $S1$ and $S2$ act as delegate to object $P2$.

9. **Polymorphism**: In object-oriented programming, *polymorphism* is the concept where a common purpose in the superclass object is denoted by instances of many different subclasses with the same function but different behavioral characteristics. Thus, an instance of the superclass can be represented and described with one subclass instance during the runtime of an event. For example, let there be a superclass name $Aircraft$. An $Aircraft$ have a pressure control system that varies according to its consisting subclasses: $Take\ off$, *Cruise*, *Landing*. Also, assume that $Aircraft$ has functioned name *cabin* $Pressure$ formulated in object $Aircraft$ and inherited to each stated subclass. When the function is called on $Take\ off$ class, Object $Aircraft$ shows the *pressure* according to the formulation made in class $Take\ off$. Similarly, if a function is called on *cruise*, Object $Aircraft$ displays and characterized according to the pressure of *cruise* state. This gives many forms of object $aircraft$ according to the instances of its subclass; which is known as polymorphism conformation of an object $Aircraft$ in object-oriented modeling.

4.2 Techniques for Object Oriented Modeling

In general, methodology concern for modeling of a system or an object design differs according to the types of requirement and real-world environment.There are several concept for modeling as mentioned above. Due to this, selection of the concept is identified in the initial stage by exploring the physics of the system and procedure involved according to the semantic need and conceptual boundaries predefined by the conceptual behavior of the system.

In a successive determination of conceptual modeling method, the notion of system/object development is gradually specified by a series of multiple phases. Which varies according to the different concept but it is also possible that key initial instructions to be followed may remain similar. Here, due to specific case formulation for ECS system, emphasis in Object-oriented system design and modeling technique is primarily prioritized due to its high-level property in reusability, extensibility, and robustness.

1. **Step 1 - Analysis :** Analysis is the first step that is concerned with devising a precise, concise, understandable and correct model of the real-world[26]. Analysis begins with problem statement which summarizes "*what has to be done*" rather than "*how it is done*". Analysis necessarily represent the statement of needs, not a proposal for a solution. In doing so, requirements has to be examined which asserts following features,
   - Problem scope
   - What is needed
   - Application context
   - Assumptions
   - Performance needs
   - Identification of constraints
   - Flexibility
2. **Step 2 - Overall Organization of system :** In this step, the focus is put on "*how the problem is solved*" before overall structure and style are decided. This includes breaking down components in different subsystems. That encompasses following decision:
   - Identification of system topology
   - Identification of link
   - Identification of association
   - Sub system partitions
   - Preparation of event flow diagram
3. **Step 3 - Detail organization of system :** In this step, the system architecture of different sub systems are implemented which includes following decisions[28]:
   - Identification of concurrency inherent in the system
   - Allocation of subsystems to its responsible task
   - Identification the approach for management of data stores
   - Choose implementation of control in software
   - Handle Boundary conditions
   - Set trade-off priorities
4. **Step 4 - Design Implementations :** This step is evolved after the detailed system architecture as presented in step 3, which involves the following process :
   - Give external inputs to the each responsible components
   - subsystem verification and validation

- Augmentation of result
- System calibration and model validation
- Optimization
- Reiteration

After these steps, analysis of the implication is made and stated them rigorously in order to simplify the model further.

4.2.1 Systematized Methods

Over the period, different methods have been propounded for constructing a high level of model representation and building system models. The main focus of all these systematized modeling methods is to simplify the complexity of large models and reduce the effort by reusing model components. Such, systematized Object-oriented technique are [11]:

1. **Deductive Modeling**: Models are created based on an understanding of the physical or artificial process where the behavior of the system is deduced from the application of natural laws expressed in a model of the system.

2. **Inductive Modeling**: When the internal process lacks complete knowledge and may not be available to the extent that would be needed for physical modeling. Under such circumstances, a hypothetical mathematical model is proposed by observing the system behavior and adapted to the model. This is called inductive modeling.

3. **Traditional Approach** : The traditional method for physical modeling is made up of three phases, which are [11]

    - Baic structuring in terms of variables
    - Stating equations and functions
    - Converting the model to state space form

4. **Object-Oriented Component-Based Approach**: Firstly, the system is understood and decomposed in a hierarchical top-down manner, which adopts following approaches[11].

    - Define system
    - Decompose system into subsystem
    - Define communication
    - Define Interface
    - Declare new model classes for all model components
    - Declare possible base classes for increased reuse and maintainability by extracting common functionality.

5. **Top Down modeling**: This method is used when the system can be understood and a set of system component library is available. The approach starts by defining the top level component and gradually decomposing to the subsystems.

6. **Bottom Up Modeling**: This method is used when the application is less known or all system components are not available in the library. It starts by formulating equations of the sub-systems component and later add more component to describe the complete system.

5 Modelica Language And TTECCS Library

Modelica is an Object-oriented programming language that distinguishes all of the features described in section4.1. In Modelica programming concept, object orientation is primarily used to structure the *model* which are built from *classes*. According to *Peter Fritzson* [11], there are four main aspects that give the distinct identity of Modelica as an object-oriented equation based programming language oriented towards computational applications with high complexity requiring high performance. They are :

- Modelica is based on equations instead of assignment statement. This permits acausal modeling that gives better reuse of classes since equations do not specify a certain data flow direction.
- Modelica has multi-domain modeling capability, meaning that model components corresponding to physical objects from several different domains can be described and connected.
- It is an object-oriented language with a general class concept that unifies classes.
- It has a strong software component model, with constructs for creating and connecting component.

In the *Modelica* language the *use* of declared items is independent of the order in which they are declared except for function parameters and record field variables[11]. Thus variables and classes can be used before they are declared. This further contributes to hierarchical modification and reuse of variable declarations from partial classes to extend and redefine the behavior of the class.

Since Modelica is an equation based language, all the declared variables are the function of the independent variable *time*. And, each equation in Modelica generates a relation in the form of declaration, in which attributes assignments are represented as equations and connection between objects generate equations. Equations in *Modelica* can be classified into four different categories which are[11],

- Normal Equation: Equation of sections, including connecting equations
- Declaration Equation: Part of the variable, parameter, or constant declarations
- Modification Equation: Equations that are used to modify attributes
- Initial Equation: Equations used for the initialization of problems

5.1 Open Modelica

Open Modelica is an open source simulation environment for *Modelica* language built models. It acts as a compiler or interpreter for *Modelica* models. *Graphical model editor*, *editor for textual model* are built within the tool to facilitate the programming and simulation environment. *Models* can be created or libraries of the model are imported, which is further translated by solving equations of the models to simulate the models/system.

The translation process occurs in different stages. The equations written in the form of the code are first translated to a *flat code*. This phase performs the checking part of the written code (*Source Code*), lookup any typing error as well as checks if the set of declared equations, functions, import statement and the structure of the model is up to the existing object-oriented structure. This process is called *code instantiation*, also called elaboration of source code. After elaboration, *equations* written in form of code are analyzed by ANTLR (Another Tool for Language Recognition) and semantics of the model is optimized by a computer processable Natural semantic language called RML(Relational Meta Language) from which *C* code is generated and fed through a *C* compiler to produce executable code.

The structure of the *Open Modelica* GUI is delineated according to the *Package* concept. *Package* contains definition of a classes including all kind of the restricted classes, functions and sub package. These packages are used for constructing libraries of reusable model definitions in hierarchical order as seen in figure 14.

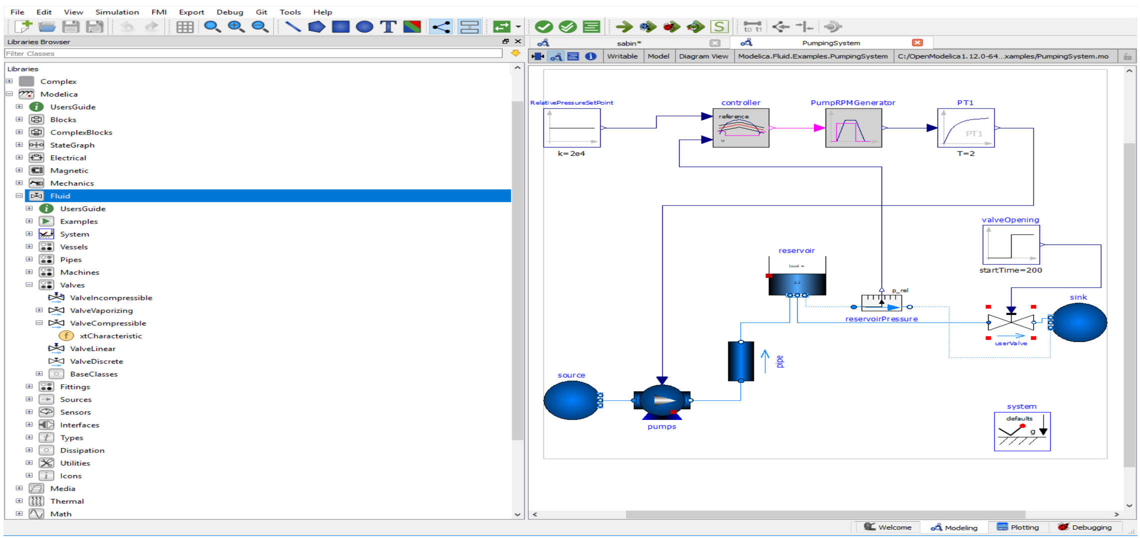

Figure 14: Screen shot of user interface of an Open Modelica

In the figure, Left side, Modelica (*MSL*) is the name of top-level package, *a library*, that is made up from sub package such as Blocks, Electrical, Magnetic, Mechanics, Fluid. These sub packages are made up of from several component models that consist constant, types, connectors, classes, functions and partial models from various engineering area, which can be reused.

5.2 Free Version of TTECCS Library

TTECCS is a comprehensive open source library (package) built in *Modelica* language designed for modeling and simulation of ECS of an aircraft. It is composed of general components and fluid domain (*Medium*) required for top-level system modeling of the ECS.

The library is founded upon the realization of the fundamental first physical principles of modeling based on conservation of mass, energy, and momentum. The conservation of mass is described by the continuity equation statement, that is, change of mass Δm in the control volume must be equal to the difference between the mass Δm_{in} entering the system and the mass Δm_{out} leaving the system since mass is neither destroyed or created in the control volume.

$$\Delta m = \Delta m_{in} - \Delta m_{out} \tag{74}$$

Conservation of the momentum is described by the statement of momentum balance from Newton second law of motion, that is, the vector sum of the forces F on an object is equal to the mass m of that object multiplied by the acceleration a of the object.

$$F = ma \tag{75}$$

Conservation of the energy is described by the first law of thermodynamics statement, the change in internal energy of control volume is equal to the heat added to the system minus work done by the system.

$$\Delta E_{c.v}, \Delta E_{in} - \Delta E_{out} + (\Delta Q - \Delta W) \tag{76}$$

Where, $\Delta E_{c.v}$= Change of energy in the control volume
ΔE_{in}, Energy entering the control volume
ΔE_{out}, Energy leaving the control volume
ΔQ is heat energy transferred to the control volume and ΔW is the net work done by the control volume on the surroundings.

The characteristics of the fluid domain in presence of physical component such as pressure drop, friction losses, heat transfer are also modeled in the library based on empirical correlation and interpolation. The relation introduced for pressure loss in the required components in the library are :

$$\Delta p_F = \zeta * \rho * \left(\frac{U^2}{2}\right) \tag{77}$$

Where, Δp_F, Frictional pressure drop
ζ, Friction coefficient
U, Velocity
ρ, Density of the medium

And, for the flow length dependent Pipe friction coefficient the equation used is

$$\lambda_F = \frac{\Delta P}{L} * \frac{2D_h}{\rho u^2} \tag{78}$$

where,
λ_F, Pipe friction coefficient

The heat flow rate across the control volume solid wall is calculated according to the following equation

$$\dot{Q}_W, \alpha A_W \left(T_W - T\right) \tag{79}$$

where,
$\dot{Q}_W$, Heat flow rate across the control volume
α, Coefficient of heat transfer
A_W, Wall surface area
$(T_W - T)$, The temperature difference between the wall surface and the ideally mixed fluid

5.2.1 Modeling Details

The modeling details in the library components include finite volume discretization, staggered grid approach and performance maps representation for selected components. In each component model, the user has the option to choose the detail level that is labeled by *Detail Level* 1, *Detail Level* 2, *Detail Level* 3. According to detail level, a user has freedom for discretization of the control volume, input geometric parameter that is used to define physical properties and correlations in each component such as, length of the pipe, pressure drop, frictional coefficient e.t.c, .

In finite volume method, the domain is divided into discrete control volumes and a finite element is created around a computational node, in which conservative properties are stored. The stored equations are then, integrated over the control volume to yield a discretized equation at its nodal point. The discretized equation at each nodal point represents a set of algebraic equations that need to be solved. For the approximation of the properties of the fluid in the element boundaries, the upwind scheme is utilized by the developer which has the capability to take an account of flow direction[29].

The *staggered* grid approaches are used to solve momentum equations. In *staggered* grid arrangement velocities are stored at the cell faces of the control volume and the discretized momentum equations are solved on the staggered control volume[29]. Meaning, the scheme divides control volume into two groups: volume and flow models. The volume model solves conservative equation (mass) whereas flow models compute the transport equation(momentum).

The performance map representation provides the flexibility for the user to simulate the model according to the known behavior of the component by inserting data in a tabular pattern. This allows the user to extend the scale of performance validation for different operating conditions with the experimental performance data *(The performance map data can be the sourced from the measurement of an actual component or can be excerpted from experimental data)*. It is usually preferred when the simulation speed is critical or if the physical processes are too complex to be captured.

Most components are behavioral models, where the model behavior is not the result of the formulation of physical equations, but other statements that produce similar behavior as if a physical process were modeled.

For the fluid (*medium*) properties details, the frameworks of the medium models are categorized into Liquid, Air and Two-phases. Which is designed for general compatibility with the fluid property interface of the Modelica Standard Library.

5.2.2 Organization of library

The library components are structured in a way, such that users can access the model inner functionality and read the source code. The organization and arrangement of the library is done by dividing the main domain into sub packages corresponding to various component types. Each subpackage component is classified according to similarities in physical properties and dependency with each other. Figure15 displays the packages, sub packages, components model in hierarchical order.

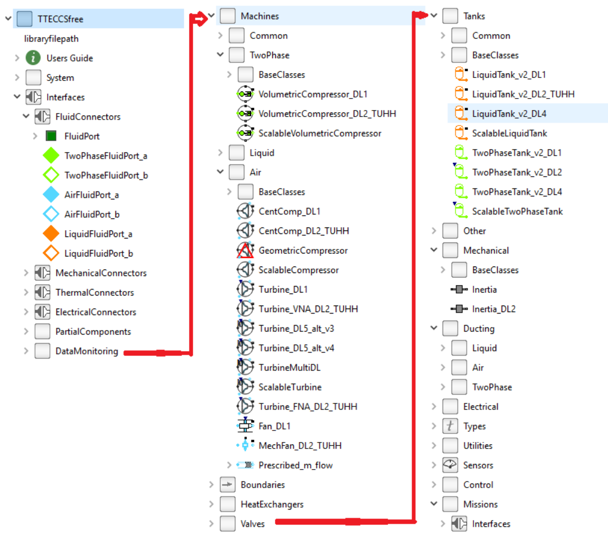

Figure 15: Screen shot of TTECCS library packages, sub-packages, component placement

Note: In the figure, red line is guided to depict order of the library from top to bottom. As can be seen, it can be noticed that *TTECCS*, is the name of the main package which comprises several sub package such as Machines, Valves, Ducting, Sensors, Control e.t.c,. Each subpackage content component model is classified according to Air, Liquid, and Two-phases. For example, subpackage labeled as Machine consist of packages classified according to the properties of the fluid. Within that, the component model of Turbine, compressor, fan are included.

5.2.3 Verification of selected components

During the modeling process of any physical system, it is crucial to check the degree of fidelity of simulation models to the real system. So far in here, objective is to model the ECS system such that it can correspond to the real system. To achieve at least reasonable accuracy and determine the theories and assumption underlying the model representation behaves correctly. An approach taken here to verify the model is done by formulating theoretical equation in MATLAB with exact same input parameter values to initialize and comparing output results with simulation results of the component model from TTECCS library.

Equations from chapter three are taken for each respective component to model the properties in MATLAB. The purpose in doing is also to ensure that the component required to develop the ECS system from TTECCS library behaves according to the theoretical concept and equations, as a part of component verification.

1. **Pipe/Duct** : There are three types of duct modeled for air to air, each labeled as *Detail level 1, Detail level 2 and Detail level 4* in TTECCS library. In *Detail level 1* setting, no pressure drop or energy exchange with the ambient is taken into account. In *Detail level 2*, it is modeled with steady-state lumped mass, energy and momentum balance equations. The user has the freedom to control the size and volume by defining the length and diameter of the duct. The default pressure drop is calculated from the standard LTS pressure drop correlation. Also, the user has an option to change the value of the pressure drop coefficient and pressure drop exponent. In *Detail level 4*, The mass and energy balances are dynamic that can be discretized by the parameter *'n'* into equally discrete volume elements and other features includes as same as in the *Detail level 2*. For further use in this work, *Detail level 2* is considered.

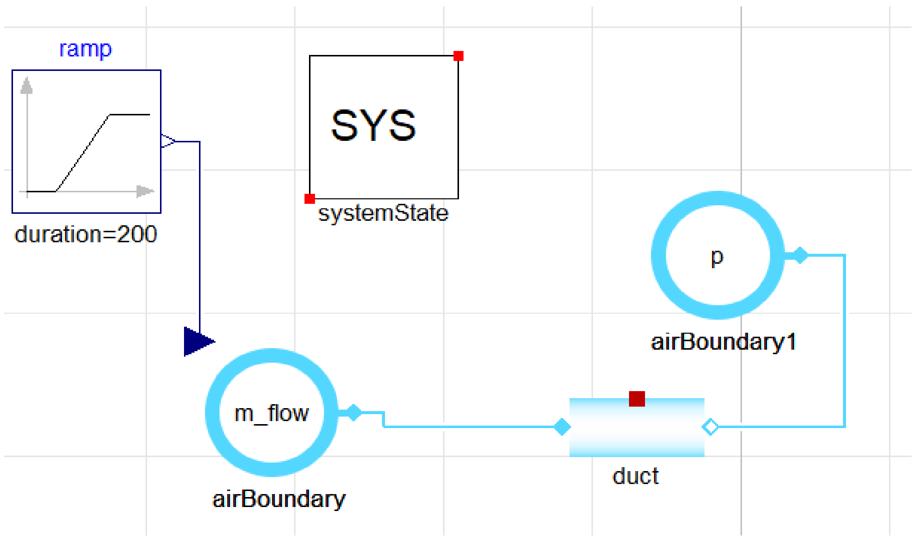

Figure 16: Screen shot of schematic illustration of duct modeling *Detail Level 2* from TTECCS library to verify its behavior

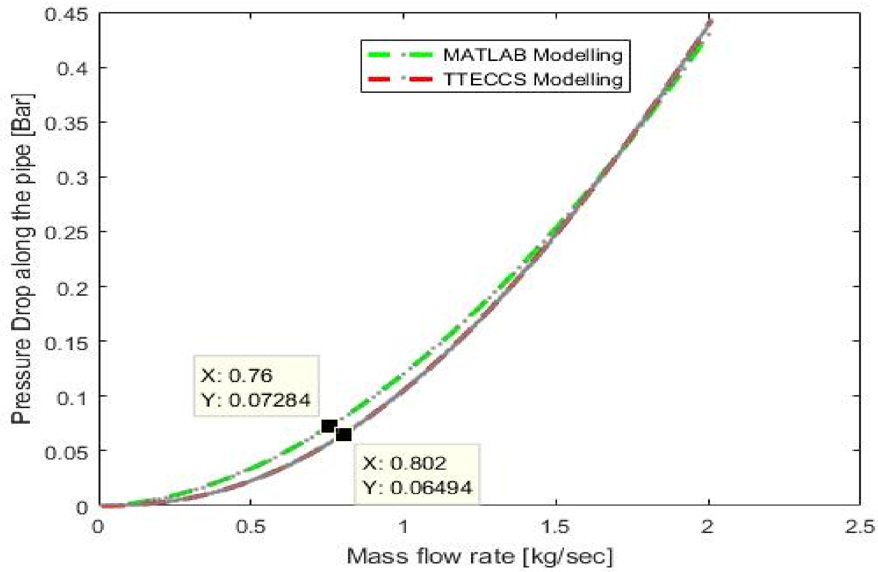

Figure 17: Pressure drop along the pipe of 10[m] in length, Diameter of 0.08[m] for various mass flow rate, Calculated parameter values and MATLAB formulation is provided in APENDIX 1

From figure 17, it can be seen that pressure drop calculation from MATLAB and simulation from Dymola in the refereed volume of pipe for various mass flow rate exhibits the same behavior. It can also be noticed that below 1.4[kg/sec] of mass flow rate, a small variance of equality in result can be seen. This is due to the change in *defined parameter values* of pressure drop exponent('α') in TTECCS duct component during simulation. The default value of 'α' which is *2* is changed to *2.26* to tune the pressure drop behavior for high Reynold number which is *1448800.72* for *2* [kg/sec] for mentioned dimension of the pipe.

In MATLAB calculation, the frictional losses in the pipe strongly depend upon the Reynold number (from equation 7) which contributes to the overall pressure drop. As the Reynold number increases pressure drop along the pipe increases. However, in TTECCS component simulation, the default value for pressure drop exponent is *'2'* according to LTS correlation. Due to this reason, 'α' is increased such that, simulation results align with the mathematical formulation. Also, it is worthy to note that pressure drop in the pipe from the TTECCS component simulation is independent with the length of pipe which can have a significant effect if the surface roughness of the pipe is very high (Reference figure 18). Because of this, it is necessary to calculate flow properties mathematically, so that one can simulate with the precise behavior according to the flow properties by interchanging the default value of pressure drop coefficient 'K', which can be an iterative procedure.

Indeed, the difference in results between two plot in figure 17 can be narrated as a statistically not significant and behavioral pattern is the same. Thus, simulation results exhibit precise behavior to the mathematical simulation with

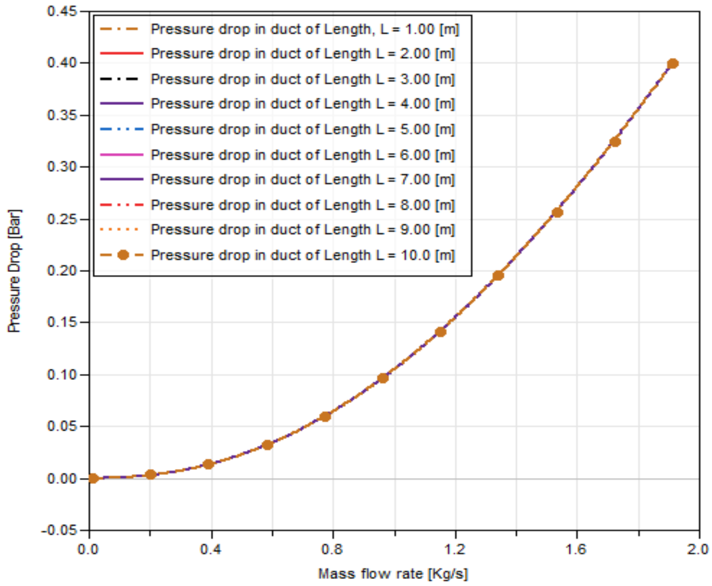

Figure 18: Pressure drop along the pipe in various different length, Diameter of 0.0254[m] for various mass flow rate of TTECCES library component 'Duct'

user-defined values which can be done by interchanging default 'α' or pressure drop coefficient 'K' in the component setting.

2. **Heat Exchanger**: *Heat exchangers* in TTECCS library package are categorized based on the medium. Sub-packages of package *Heat Exchanger* are labeled as *Two phase to air, Liquid to Two-phase, Air to Air,* and *Liquid to air*. Each sub packages are further classified according to the detail of the modeling level. Here, By considering the use of heat exchanger in this work, only air to air sub packages are studied for further use.

   In *Detail level 1* setting, user has the freedom to control the effectiveness of heat exchanger with user input effectiveness value of the non-phase changing fluid. Mass and energy balances are in steady state and pressure loss is neglected by default, providing user freedom to set pressure drop optionally and independently for hot and cold side through the parameters *use hot pressure drop*, and *use cold pressure drop* respectively in component setting [30]. Where, heat exchanger effectiveness is formulated by the following relation, Equation 80.

$$\epsilon_h = \frac{\dot{W}(T_{h,i} - T_{h,o})}{\dot{W}_{min}(T_{h,i} - T_{c,i})} \tag{80}$$

   where,

$$\dot{W} = \dot{m}_i * C_{p_i} \tag{81}$$

   Where,
   ϵ_h,Effectiveness of heat exchanger
   $T_{h,i}$,Inlet temperature of hot side [K]
   $T_{h,o}$, Outlet temperature of cold side [K]

$\dot{W}$, Heat capacity rate in [W/K]
$T_{C,i}$, Inlet temperature of cold side
m_i, Mass flow rate [Kg/sec]
C_{p_i}, Specific heat capacity at constant pressure [J/(Kg K)]

In *Detail level 2* setting, heat exchanger effectiveness is read from two-dimensional performance map and computes further as a static model. In *Detail Level 3*, it includes dynamic mass and energy balances in the fluid domain in which component effectiveness is read from the performance map as a similar procedure to detail level 2.

Due to difficulty in finding comparable data for a performance map to adopt in TTECCS library component, *Detail level 1* is used here for this work. The overall efficiency of the heat exchanger is calculated according to the mathematical formulation from chapter three.

In order to validate the component behavior, inlet mass flow rate and temperature are set in hot side and cold side of the component with overall heat exchanger efficiency of 25.89 percent in TTECCS as shown in figure 20. It can also be seen from the figure, outlet temperatures of the heat exchanger from MATLAB modeling and component simulation exhibits similar behavior. Thus, it can be said, TTECCS component behaves precisely to the theory according to the user-defined efficiency.

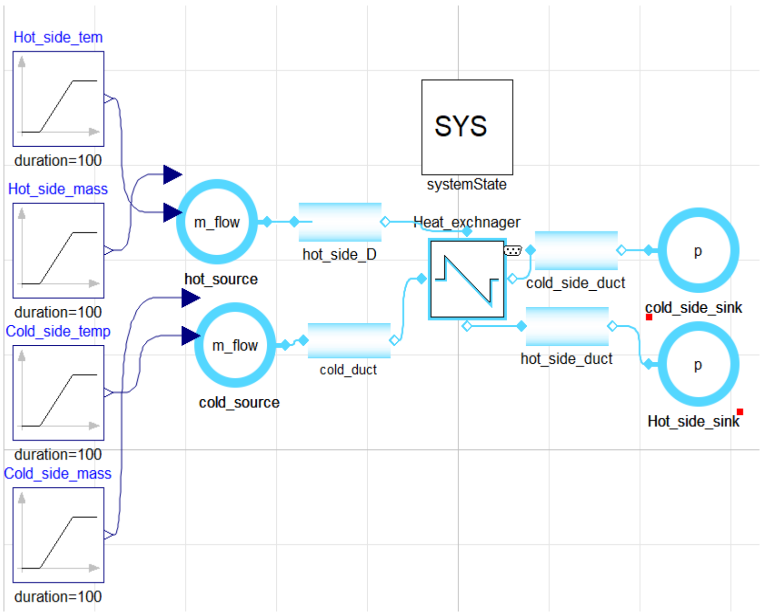

Figure 19: Screen shot of schematic illustration of heat exchanger modeling *Detail Level 1* from TTECCS library to verify its behavior

.

3. **Turbine and Compressor**: Modeling details for turbines and compressor are also categorized according to the detail level. In *detail level 1* of these components, the user can set pressure ratio and efficiency that defines the

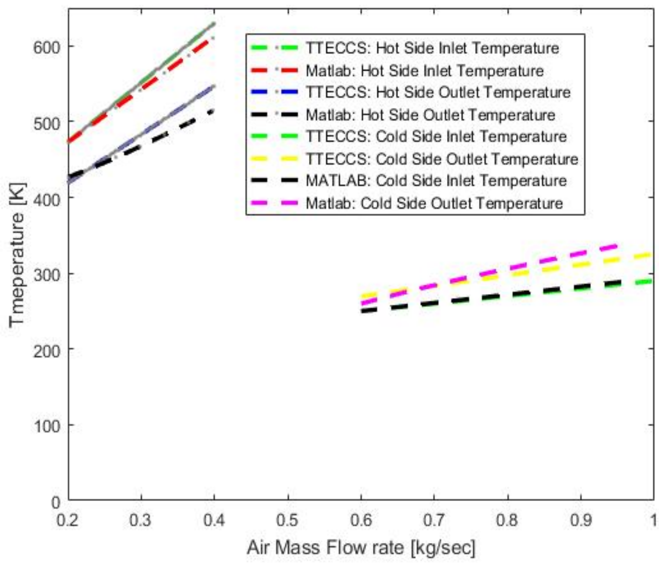

Figure 20: Inlet and Outlet temperature of Heat exchanger from TTECCS component simulation and MATLAB mathematical formulation

[Note: MATLAB mathematical modeling and parameters input variables are provided in Appendix 1]

basic function of both components. Component behavior is independent of the rotational shaft speed. Shaft power is computed from mass flow rate, efficiency and pressure ratio.

In *detail level 2*, component are modeled in reference to air cycle centrifugal model. Parameters that interpret the function of the compressor is represented by *Performance map*, where the user can define the operating range of compressor according to the availability of data.

Detail level 1 of the compressor is used within this work and equation 68 is taken into consideration to verify its behavior. This approach follows under the isentropic process assuming constant specific heat. After simulation of the component, results are observed to check if it follows the theoretical behavioral according to equation 68.

In doing so, compressor efficiency in the component are set manually and checked if the right-hand side of the equation 68 is equal to the left-hand side after the simulation. Pressure ratio in the right side of the equation 68 is set to*'4'* with varying (*eta set*) efficiency range in the component(*These value are approximated from the performance map found in website enginelab.com for Borgo Warner Turbo Systems[31]*). After the simulation temperature ratio is calculated considering the constant inlet temperature of *'283 [K]'* and outlet from the simulation result as shown in figure 22. Table 5 illustrates the deviation in right hand side of equation 68 From Table 5 it can be said that component follows theoretical behavior according to the equation 68 and has the capability to simulate precisely if top-level parameter *pressure ratio* and

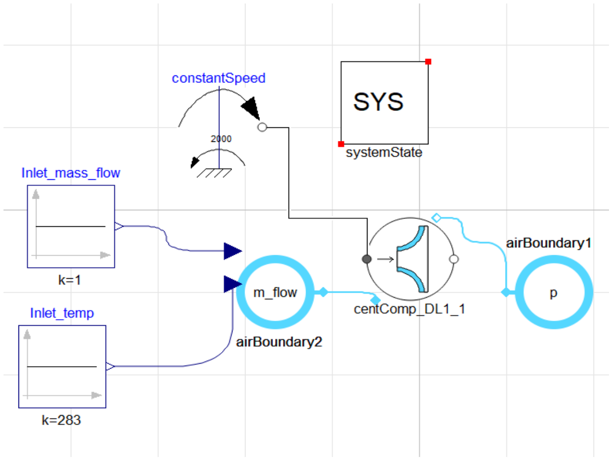

Figure 21: Screen shot of schematic illustration of compressor model *Detail Level 1* from TTECCS library to verify its behavior

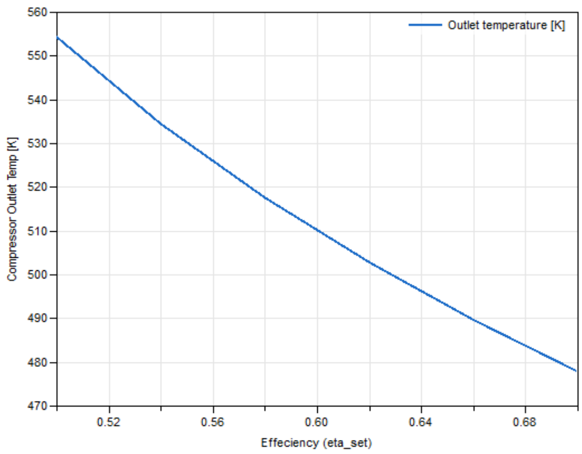

Figure 22: Simulation results of compressor component with varying efficiency with constant pressure ratio

isentropic efficiency of the compressor is known.

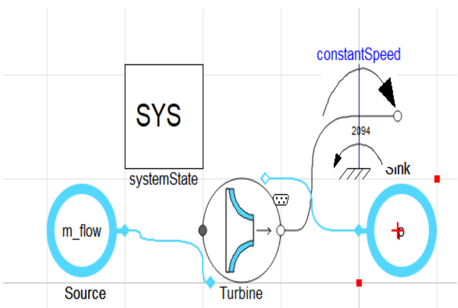

Figure 23: Screen shot of schematic illustration of Turbine model *Detail Level 1* from TTECCS library to verify its behavior

Similar approach as compressor is employed to verify the behavior of turbine model *Detail Level 1*. Figure 24 depicts the simulation results illustrating the

Table 5: Deviation in temperature ratio with respective efficiency value according to equation68, [Note : For the right hand side of the equation, pressure ratio is set constant for each efficiency ratio in component]

Left hand side of Equation68	Right hand side of Equation 68	Deviation
0.5	0.5008	0.16%
0.52	0.5204	0.0769
0.54	0.54	0
0.58	0.58	0
0.62	0.62	0

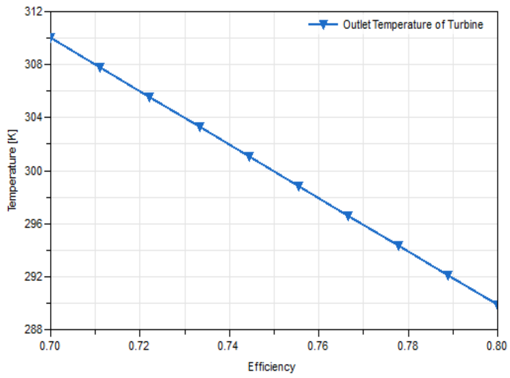

Figure 24: Simulation results of Turbine component *Detail Level 1* with varying efficiency with constant pressure ratio

behavior of turbine while varying efficiency. During the simulation, it utilizes constant overall pressure expansion ratio of *'8'* and inlet Temperature of *'450 [K]'*.

Figure 24 illustrates when the overall efficiency of the turbine increases the temperature drop increases. Thus, component corresponds to the theoretical behavior to equation 73.

4. **Air valve** : Air valve in TTECCS library are extended from MSL. Therefore, validation is referenced to validation of air valve in thesis work [32]. The equation presented in chapter three, section 3.1.3 can be utilized to understand the working principle of the valve.

5. **PID Controller**: PID is used from MSL. All the components in MSL are verified and validated by Modelica and the Modelica Association. All the mathematical concepts that are used to formulate PID component in MSL library are excerpted from the book *PID controllers by Karl J Äström and Tore Hägglund, second edition*. Chapter two and three of this book can be referenced, which is available freely in PDF version online.

6 Modeling of ECS And Simulation

In this chapter concept introduced in the previous chapter are utilized to develop a comparatively simple analytical model of an ECS to explain its behavior. And, phenomena characterized by components in ECS are briefly discussed to generalize the response of several component variables. Additionally, the desired behavior and undesirable behavior of the ECS are discussed.

6.1 Results

- **Ideal case I**

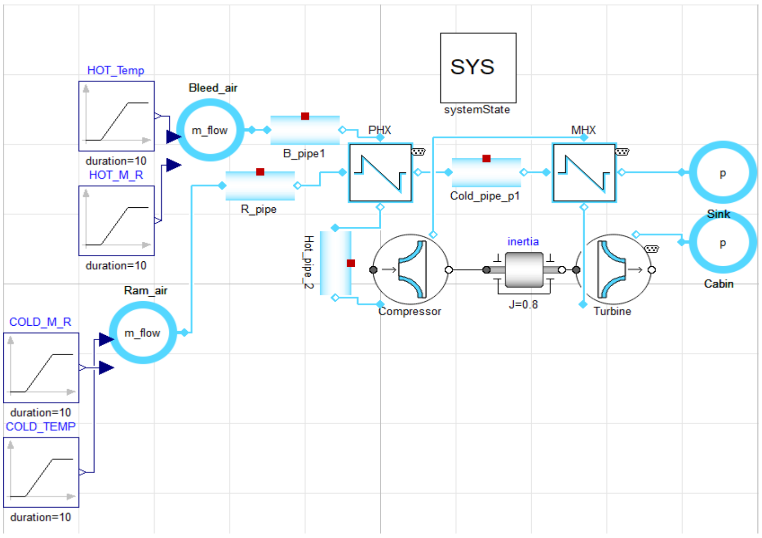

Figure 25: Ideal ECS Architecture without control system

User defined values		
	Temperature [k]	Mass flow rate [Kg/sec]
Bleed Air	574	0.4
Ram Air	287	0.9

	Effectiveness
PHX	0.5
MHX	0.40
Compressor	0.6
Turbine	0.9

Figure 26: User Defined values for given parameter in an ECS architecture 25

	PHX		Compressor		MHX		Turbine	
	Inlet	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*
Tem[K]	574	430.5	430.45	582.47	582.47	490.392	490.392	279.85
Pressure Drop [bar]	- 0.160		+ 5.080		- 0.18		- 9 .03	

Table 6: Temperature and pressure along the ECS architecture 25 with user defined values in 27*Note: Initial absolute pressure from the source is 5.25 bar*

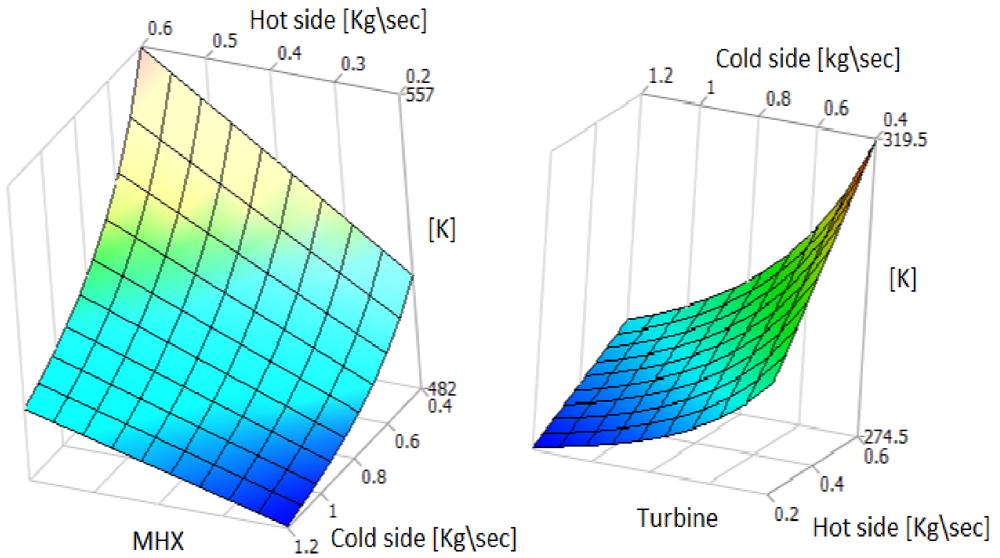

Figure 27: Performance map of MHX and Turbine with respect to outlet temperature in each component while varying inlet mass flow rate in an ECS architecture of figure 25 with setting mentioned in figure 26

.

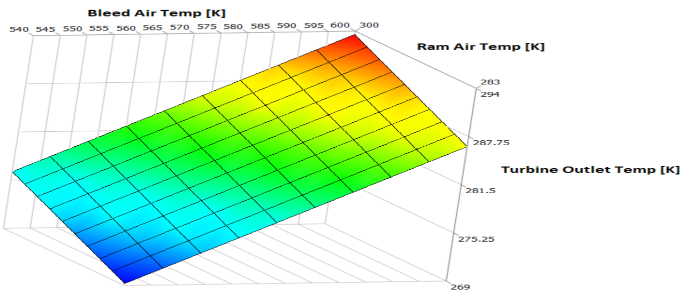

Figure 28: Performance map of overall system with respect to inlet temperature of cold side and hot side in an ECS architecture of figure 25 with setting mentioned in figure 26

.

- **Ideal Case II**

In figure 25 and 29, each component within an ECS are integrated to asses the

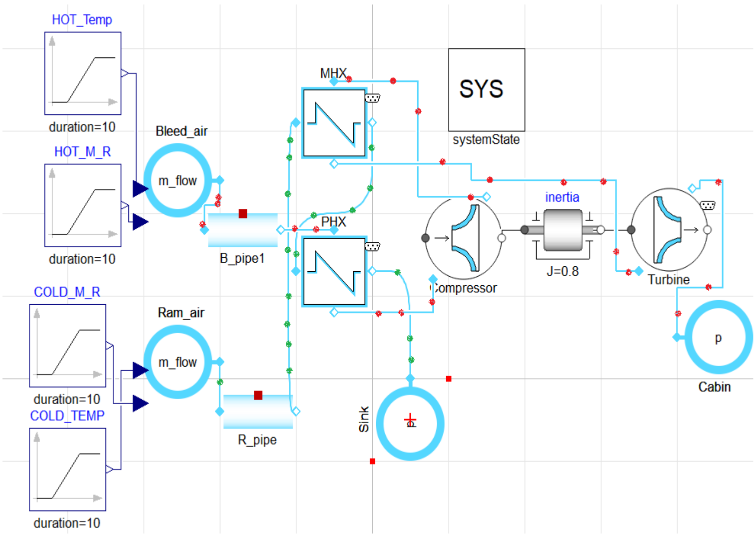

Figure 29: Ideal ECS architecture without control system that replicate the conceptual design of cooling pack in figure 9

.

	PHX		**Compressor**		**MHX**		**Turbine**	
	Inlet	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*
Tem[K]	574	493	493	665.47	665.47	442.51	442.51	257.574
Pressure Drop [bar]	- 0.155		+ 4.57		- 0.160		- 9	

Table 7: Temperature and pressure along the ECS architecture 29 with user defined values in 27*Note: Initial absolute pressure from the source is 5.25 bar*

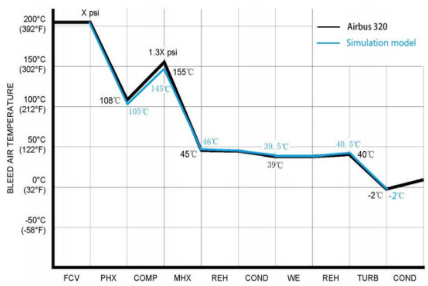

Figure 30: Inlet temperature and outlet temperature along each component in Airbus A320, excerpted from [7]

.

behavior of an ideal ECS, i.e. without any control system. Due to limited information on actual flight condition data for each component, an ideal gas is used as a medium. Input parameters values as given in figure 27 are estimated first by sweeping the parameters values to develop a performance map of each component. From performance map, values are acquired such that it can exhibit desired behavior consistently(*Temperature in each component is referenced to Airbus A320 as in figure 30 but in a higher magnitude of bleed air temperature*).

In ideal case I figure 25, ram air is first passed to the primary heat exchanger and main heat exchanger subsequently. In contrast to the ideal case I, ram air enters to primary heat exchanger after passing through the main heat exchanger in ideal case II.

In both cases above, temperature behavior is comparable to the temperature behavior of Airbus A320 as shown in figure 30. Thus, the physics behind each input parameters of each component is calibrated from these two ideal cases.

Simplified analytical ECS model III

- **Architecture I**

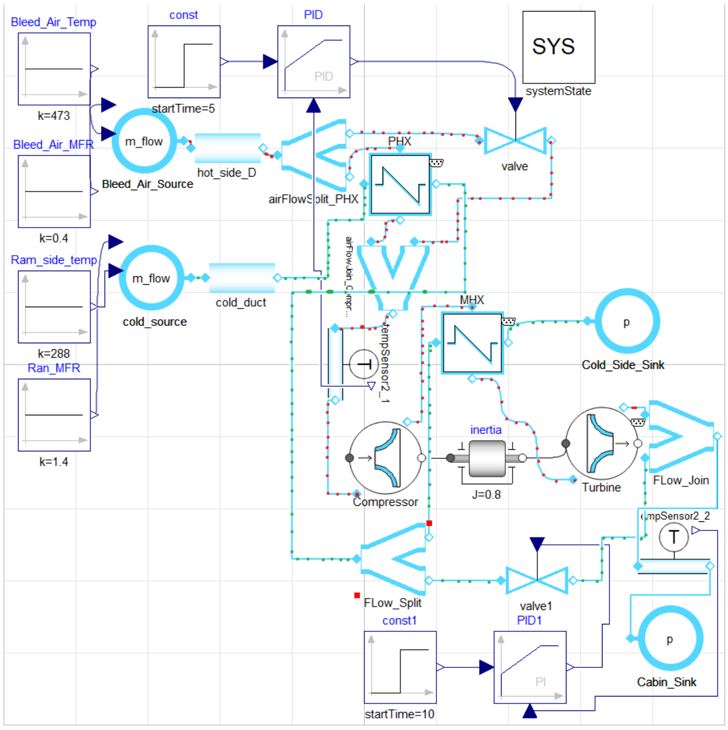

Figure 31: Simplified ECS architecture with temperature control system assuming constant inlet temperature, mass flow rate and pressure with components setting shown in Table 8

Figure 31 presents the simplified ECS. The approach behind ECS architecture is based on the idea, such that it can control the mass flow rate subsequently temperature. The ECS arrangement layout is similar to above ideal case II. Bleed air is extracted from the engine and cooled down in PHX and MHX respectively. Some of the bleed air is bypassed through *valve* as seen in figure 31 to achieve a set temperature ahead of the compressor. To regulate the temperature inside the cabin, the second bypass line is added in the ECS architecture functioned by *valve 1*. Both of these valves functions by controlling the mass flow rate depending upon the desired temperature that is set. Temperature drop and pressure drop along each component

	User Defined Values
	Set_Effectiveness
Primary Heat Exchanger	0.50
Main Heat Exchanger	0.35
Compressor	0.70
Turbine	0.90
Turbine Expansion Ratio	6
Compressor Pressure Ratio	2

Inlet Temperature
[K]
Hot Side 473
Cold Side 288

Mass Flow rate
[Kg/sec]
Hot Side 0.4
Cold Side 1.4

Table 8: User Defined values for mentioned parameters in an ECS architecture 31

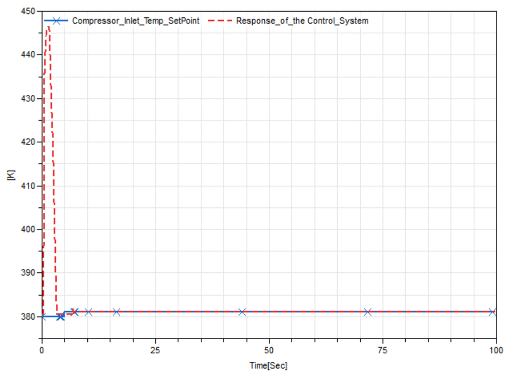

Figure 32: Inlet temperature to compressor of an ECS architecture of figure 31

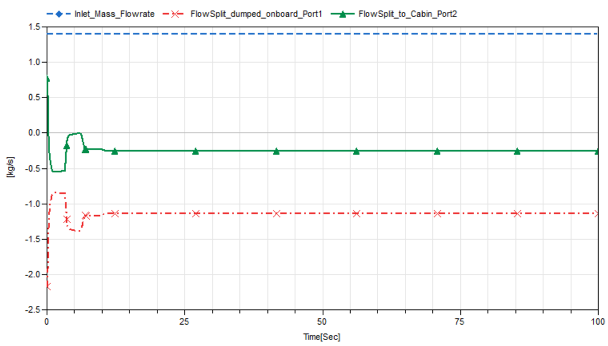

Figure 33: Bypassed flow to cabin controlled with Valve1(*Trim air control valve*) as shown in figure 31

	PHX		**Compressor**		**MHX**		**Turbine**	
	Inlet	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*	*Inlet*	*Outlet*
Tem[K]	473	379.5	381	577.105	577.105	485.05	485.05	276.122
Pressure Drop [bar]	- 0.04		+ 6.07		- 0.04		- 8.07	

Table 9: Temperature and pressure along the ECS architecture 31 with user defined values in Table8*Note: Initial absolute pressure from the source is 3.43 bar*

are illustrated in *table 9*. Although pressure regulating valve is not configured in ECS architecture *figure* 31, pressure in presumed cabin (*cabin sink*) is near ambient

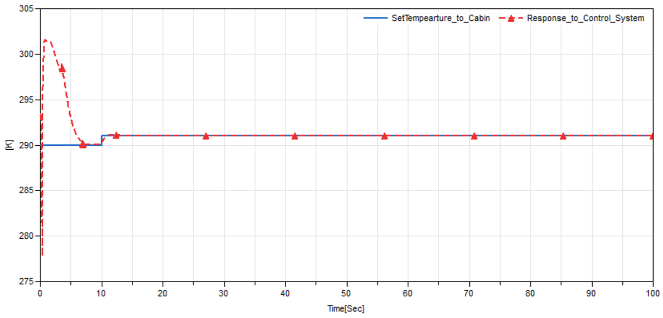

Figure 34: Inlet temperature to preassumed Cabin(*Cabin Sink*) of an ECS architecture of figure 31

with component setting presented in *table* 8.

As shown in figure 32, by utilizing the PID controller, the desired inlet temperature is set to 381 K ahead of the compressor in the ECS architecture figure 31. PID controller output sets the position of *valve* according to the feedback given by the temperature sensor in the ECS architecture. Then, based on the error and PID controller tuning constants, PID controller opens the appropriate position of *valve* for keeping the temperature to the set point. In an identical way desired temperature in the presumed cabin is set to 292 K. This is controlled by PI controller *PID1* in figure 31. Based on the difference between set point and feedback from the temperature sensor and PI controller tunning constant, *valve1* opens to the appropriate position to maintain the setpoint temperature. Figure 33 depicts the hot mass flow rate bypassed from *valve1* to maintain the desired cabin temperature. Correspondingly temperature in presumed cabin *cabinsink1* is presented in figure 34.

During initialization of the simulation in the ECS model figure 31, it produces valid results only within a certain range of input values that are set from *table 8*. This is mainly caused by the theoretical physical constraints of the components; for example, efficiency in the component *heat exchanger* is defined by the hot side which limits to the physical input *mass flow rate* or *temperature of cold side* in the system. Similarly, *expansion ratio* in the turbine is set relatively high. This is because the mass flow rate set is associated with the heat transfer rate coefficient. With the reduction in mass flow rate and temperature influences the volumetric flow rate which correspondingly decreases the heat transfer coefficient then decreases the capability to expand the airflow to drive the turbine. This limits the generation of power to counterbalance the optimum rotating speed of the turbo-compressor shaft required to drive a load, that is, desire pressure ratio and efficiency set in the compressor and turbine respectively. Thus, the proximity of the expansion ratio is set by determining the sensitivity variation with the amount of mass flow rate and exit temperature from MHX while initializing the system. This can be done by allowing parameters to run parametric analysis to evaluate parameters valid range for input criteria (*mass flow rate, temperature*) in a similar manner as shown in figure 27 and 28.

Although some difference can be noticed with the results shown in figure 30, the simulation results presented in table 9 shows the expected general trend within the components. Thus, the ECS configuration in figure 31 indicates the capability to predict the temperature and static pressure behavior in each component within the ECS.

6.2 Discussion

As stated in section 1.1 modeling of the ECS in order to comprehend its behavior is not an unfamiliar work. Several approach and technique have been utilized by number of researchers in past. Daniel Perez Linares [3] have utilized Flow Master software to model and simulate simplified ECS. Similarly, Leo MÃkelÃ has developed the ECS model to understand the dynamic response of the pressure control valve. Many works in the ECS topic has been done which may give a notion of “You are only as good or even worst to your last performance”. However, understanding developed while carrying out this thesis work suggest to eliminate this school of thought because of the complexities while modeling the ECS. Use of different method/software can provide correlation of simulation cost and complexities which may help on improving existing modeling concept. Although, method (*flowchart* 1) used here makes use of abstraction and design configuration is constraint within a limited range with the number of assumptions; it is capable for developing the ECS model such that simulated result provides physical meaning predicting parameters behavior. Furthermore, through abstraction modeling, it reduces the complexity level and implementation process can be simple while running the simulation. However, more extensive analysis based on the assumptions and interactions of subsystems components is suggested before selecting the procedure.

The review of sub systems of the ECS presented in chapter 2 focuses only in context of this thesis aim. Due to this, the ECS modelled here limits the definition of the ECS to the conditional application of the ECS but concept introduced here sufficiently encompasses the core process related to define the functional ECS. After establishing the conditional model of the ECS to simulate the system; input parameters values that are determined by generalizing the equations and concepts of component operations from chapter 3 further constraint model operation. This suggests, firstly it is necessary to determine *scalability issues* of components parameters before simulating the system. Secondly, component setting should be tuned according to the specific mission of an aircraft to achieve accurate simulation results otherwise attribution of result varies compare to the operating conditions of the ECS. After recognizing these challenges, sensitivity analysis for each parameter is proposed and recommended in order to identify the range of system operation and component(*domain*) based on input parameters (*here, mass flow rate and temperature*). Thereby, revealing choice of an options for potential flexibility to make system model more efficient and to avoid compilation of system failure. Furthermore, in relation to the tittle of this thesis, an important point can be drawn, that is, configuration of the ECS can be and remains *generic* but in terms of scalability and operation of the ECS - term *generic* for the ECS may not be appropriate.

In the context of the modeling language, prior work (*other thesis work*) has evidently vocal in favor of system modeling on OOM with Modelica language. Hereby, even in this case, though the claim is subjective with limited research on other methods - the use of Modelica language supported tool for system modeling is recommended. This distinct remark is mainly made due to easement while trying to find the compilation error between system components interface or if system compilation fails. OOM with Modelica is a class-based programming language, therefore, it is easier to identify spots of errors manually by categorizing components in terms of contextual errors(in terms of equations). It also posses wide flexibility for manual modifications while analyzing the system's behaviors.

In addition to the above points discussed, TTECCS library components demonstrate a high level of source code transparency of each component which allows understanding the detail formulation of component efficiently. Thus, making TTECCS library as a desirable library to model the ECS.

7 Conclusion

- Verification of components was promising. So, the implementation of components from this library to model the ECS proves to understand the behavior of individual components, only if systems components has advanced up to a point where detailed performance data is available.
- The use of performance maps based components do allow to estimate the system behavior under varying conditions but most of the components of the system are modeled statically which limits to predicts the dynamic behavior of components.
- The ECS developed here demonstrate the functionality of each component which can be implemented to scale the mechanisms of steady-state flight situation.
- The target point is assumed to be constant for the ECS model simulation and response of the PID controller successfully attempts to maintain the target temperature. Thus, employed temperature control strategy proves to stabilize target temperature.
- The ECS model developed here is the most simplified version of the real world and many parameters were unknown. So, many questions remain to accurately model the real cabin conditions.

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A Appendix

A.1 Mathematical modeling of selected components in MATLAB

```
%% Pipe pressure drop and temperature drop calculation (note: All the
    equation are excerpted from D.S Miller book chpter 7/8. Pressure
    drop  is calculated  considering the flow as compressible flow)
%%
format longg
kv=((1.725+1.846)/2)*10^-5; % kinematic viscoity of air for 15 degree
    celsius
Ad= (1.284+1.177)/2% Air density at 200 degree celsius
gamma=1.40; % specific heat ratio at 200 degree celsius
m=0.1:0.02:2; % mass flow rate from 0.1 kg/ sec to 1.5 kg/sec
R= 8.314; % Gas Constant
T= 15; % temperature degree celsius
a=(gamma*R*T)^0.5; % velocity of the sound
d=0.12;
h=10 ;  % length of the pipe
U=m./(Ad*(pi*(d/2)^2));  % mean velocity of the air flow
Ca=pi*(d/2)^2 ; % cross sectional area of pipe
Wp=  2*pi*(d/2)*h; %Wetted perimeter of the pipe
D=(4*Ca)/(Wp); % Hydraulic diameter of the pipe
Re=d.*U./(kv) % Reynold number
k= 0.0025/1000 % roughness values for smooth pipes table 8.1 d.s.
    miller
pp=(5.74)./((Re).^0.9)%
den= log(((k/(3.7*d))+(pp))).^2 % denominator of the friction
    coffecient formula
f=(0.25)./((den)) % Friction loss coffecient of the pipe Equation 8.4 D
    .S miller book
kf= f.*h /D% pipe loss coffecient
delP=(kf.*1.31.*U.^2)/(2) % pressure loss through the  pipe

figure(1)
plot(delP*(1*10^-5),m,'b')
xlabel('Pressure Drop along the pipe [Bar]')
ylabel('Mass flow rate [kg/sec]')
```

```
%% 2) pressure and temperature modeling of Heat Exchanger
%%
%% Step 1
%%
ABT = 473:23:620% Air bleed temperature
RAM_T=250:6.5:290 %
%% Calculation of the Bleed air density
n=7
ABT_1=zeros(1,n)
for  i = 1:7
 mm  = 28.97 ;  % Molar mass of air
 RC_IC = 0.0831% IDEAL GAS CONSTNAT
```

```
P_ABT = 3700*1000 % pressure of the bleed air in pascal
ABT_1(i)=ABT(1,i)
rho_ABT(i)=( mm*P_ABT)/(RC_IC*ABT(i))
end

maQ= 0.2:0.033:0.4 %  mass flow of the bleed air kg/sec
rt= (0.007) % Radius of the tube
Lt= 10 % length of the tube
Area= 0.002% (pi*(rt^2)) % Cross sectional area of the tube
Prt=  0.54 % 2*pi*rt*Lt % Perimeter of the pipe
Dt=  4*( Area/Prt) % hydraulic diameter of the pipe
NTh= 38 % number of tubes

 % mass flow in each tube

le_he= 0.54+0.04 % length of the heat exchnager hot side
lng_pitch=0.035 % longitudinal pitch
number_tube = (le_he -Dt)/(lng_pitch);
maQT=maQ./38 % mass flow in each tube
for i=1:7
 Medrt(i)= (maQT(i))/((rho_ABT(i))*(Area))% mean velocity
end



%% Step 2 : calculation of the dyanamic viscosity

for i=1:7

S= 110.4; % sutherland constant in ke % Temeperature at kelvin

visre=1.79*10^-5;

Tref= 288.15; % temperature at sea level

vis(i)= (visre)*((ABT(i)/Tref)^1.5)*((Tref+S)/(ABT(i)+S));

end% Viscoisty % Viscosity



%% Step 3 Reynold number calculation

for i=1:7

Ret(i)= ((rho_ABT(i)*Medrt(i)*Dt))/(vis(i));

end%% Reynold number for the tube



%% Thermal conductivity of the fluid of the air reference ( http://
    bouteloup.pierre.free.fr/lica/phythe/don/air/air_k_plot.pdf)



for i=1:7
Kair(i)= (1.152*(10^-11)*(ABT(i)^3))-(4.86*(10^-8)*(ABT(i)^2))
```

```
    +((1.02*10^-4)*ABT(i)) -( 3.93*10^-4);
end %%% Thermal conductivity of the air


%% Step 4 prandtl number Calculation

Cp= (1.013*1000) %specific heat of air at  constant pressure in standtard atmosphere; for the temperature of 400K
for i=1:7;
pr(i)=(vis(i)*Cp)./Kair(i); % Prandtl Number
end

%% Step 5  Frictional coefficient of the tube

kt= 0.0025/1000 % roughness values for smooth pipes table 8.1 d.s. miller for the tube
for i= 1:7
% ppt(i)=(5.74)/(Ret(i)^0.9)%
% ll=((kt)/(3.7*Dt))
% dent(i)= (log(ll+ppt(i)))^2 % denominator of the friction coefficient formula
% ft(i)=(0.25)./((dent(i)))
ft(i)=(0.790*log(Ret(i))-1.64)^-2; % Frictional coefficient
end

 %% Step 6  Nusselt number
% numerator of the formula
pr_1=zeros(1,n)
ft_1=zeros(1,n)
Ret_1=zeros(1,n)
for i= 1:7

     pr_1(i)=pr(1,n);
     ft_1(i)= ft(1,n);
     Ret_1(i)=Ret(1,n);
     lll(i)=ft(i)/8;
     jjj(i)=(Ret(i)-1000);
     Num(i)=lll(i)*jjj(i)*pr(i);
     %Num(i)= (((ft(i))/8)*(Ret(i)-1000)*(pr(i)))
     kkf(i)=(ft(i)/(8))^0.5;
     ppf(i)=((pr(i)^(2/3))-1);% denominator of the formula
     Denoo(i)=1+(12.7*kkf(i)*ppf(i));
     Nu(i)= (Num(i))/(Denoo(i));
     ht(i)= ((Nu(i))*(Kair(i))/(Dt)); % heat transfer coffecient
end
%%

%%%%%%%%%

%%%%%%%%                         RAM AIR Properties calculation

%%%%%

%%

%% Total heat transfer area of the hot side and cold side

%% %% Calculation of the Density for RAM air
```

```
RAM_T=250:6.5:290;
maQR= 0.6:0.06:1 ;% Ram air mass flow rate kg/sec
RAM_T_1=zeros(1,n);
for  i = 1:7

    mm  = 29 ;  % MOlar mass of air

    RC_IC = 0.0831;% Idealgas constant
    P_ABT = 0.081 ; % pressure of the bleed air in bar
    RAM_T_1(i)=RAM_T(1,i);
    rho_RAM_T(i)=( mm*P_ABT)/(RC_IC*RAM_T(i))
end

%% Step 2 : calculation of the dyanamic viscosity
%%
for i=1:7
S_cs= 110.4; % sutherland constant in ke % Temperature(kelvin)
visre_cs=1.79*10^-5;
Tref_cs= 288.15; % temperature at sea level
vis_cs(i)= (visre_cs)*((RAM_T(i)/Tref_cs)^1.5)*((Tref_cs+S_cs)/(RAM_T(i)+S_cs));%Dynamic Viscosity
end

%% Velocity of ram air
Lt_cs= 10 ;% length of the tube
Area_cs= 0.002;% (pi*(rt^2)) % Cross sectional area of the tube
Prt_cs=  0.54; % 2*pi*rt*Lt % Perimeter of the pipe
Dt_cs=  4*( Area/Prt); % hydraulic diameter of the pipe
NTh_cs= 38 ;% number of tubes
maQR_medrt=maQR./NTh_cs;
for i=1:7
 Medrt_cs(i)= (maQR_medrt(i))/((rho_RAM_T(i))*(Area_cs))% mean velocity of the
end

%% Step 3 Reynold number calculation
%%
for i=1:7
Ret_cs(i)= ((rho_RAM_T(i)*Medrt_cs(i)*Dt_cs))/vis_cs(i);%% Reynold number for the tube
end
%% Thermal conductivity of the fluid of the air reference ( http://bouteloup.pierre.free.fr/lica/phythe/don/air/air_k_plot.pdf)
%%
for i=1:7
Kair_cs(i)= (1.152*(10^-11)*(RAM_T(i)^3))-(4.86*(10^-8)*(RAM_T(i)^2))+((1.02*10^-4)*RAM_T(i)) -( 3.93*10^-4);
end
%%
%% Step 4 prandtl number Calculation
%%
Cp= (1.013*1000); %specific heat of air at  constant pressure in standtard atmosphere J/kg*k For the temperature of 400K
for i=1:7
pr_cs(i)=(vis_cs(i)*Cp)./Kair_cs(i); % Prandtl Number
end
%% %% Step 5  Frictional coffecient of the tube
%%
```

```
kt= 0.0025/1000; % roughness values for smooth pipes table 8.1 d.s. miller for the tube
for i= 1:7
% ppt(i)=(5.74)/(Ret(i)^0.9)%
% ll=((kt)/(3.7*Dt))
% dent(i)= (log(ll+ppt(i)))^2 % denominator of the friction coefficient formula
% ft(i)=(0.25)./(((dent(i)))
ft_cs(i)=(0.790*log(Ret_cs(i))-1.64)^-2;

end
%% %% Step 6  Nusselt number
% numerator of the formula
pr_cs_1=zeros(1,n);
ft_cs__1=zeros(1,n);
Ret_cs_1=zeros(1,n);
for i= 1:7
    pr_1_cs(i)=pr_cs(1,n);
    ft_1_cs(i)= ft_cs(1,n);
    Ret_1_cs(i)=Ret_cs(1,n);
    lll_cs(i)=ft_cs(i)/8;
    jjj_cs(i)=(Ret_cs(i)-1000);
Num_cs(i)=lll_cs(i)*jjj_cs(i)*pr_cs(i);
%Num(i)= (((ft(i))/8)*(Ret(i)-1000)*(pr(i)))
kkf_cs(i)=(ft_cs(i)/(8))^0.5;
    ppf_cs(i)=((pr_cs(i)^(2/3))-1);% denominator of the formula
    Denoo_cs(i)=1+(12.7*kkf_cs(i)*ppf_cs(i));
    Nu_cs(i)= (Num_cs(i))/(Denoo_cs(i));
    ht_cs(i)= ((Nu_cs(i))*(Kair_cs(i))/(Dt_cs)); % heat transfer coefficient
end %% heat transfer coefficient
%% %%

%%

Kfin = 177; %% w/m^2.K -- thermal conductivity of Fin in PHX
Thf= 0.0002 ; %% mt--- Thickness of the fin
fin_h= 0.006 ; %% mt --- Height of the fin
fin_e = 0.8; % fin efficiency from the table
La= 0.35; % length of PHX
Lb=0.27;% breadth of PHX
Lc=0.15; %%  depth of PHX
sf= 0.002; % pitch of the fin
AHS= (2*NTh*Lb*Lc*((sf-Thf)+(2*fin_h)))/(sf); % Area of the heat exchanger
ACS=(2*NTh*Lb*La*((sf-Thf)+(2*fin_h))/(sf)); % Area of the heat exchanger
%%  Cold side
%% Total surface effectiveness of fin
Eft = 1-((1-fin_e)*(Area/ACS)); %% TOTAL SURFACE TEMPERATURE EFFECTIVENESS OF THE FIN
Vhx= La*Lb*Lc;
%% Specific heat constant volume
for i= 1:7
mid=(((AHS/Vhx))/((ACS/Vhx)));
    midd(i)=ht(i)*mid;
RTR(i)= (1/(Eft*ht_cs(i)))+(1/(midd(i)))+(Thf/Kfin);
% (((1)./(Eft*ht(i))))+(1./((((AHS/(Vhx))./((AHS./Vhx)).*(ht(i))))+(Thf
```

```
    /Kfin)));
end
%+(Thf/Kfin)% OVERALL THERMAL  RESISTANCE
%%  Overall heat transfer coffecient
for i=1:7
U(i)= (1/RTR(i));
end

%% Heat capacity rate for the heat both
ca= maQ.*(1005); % mass flow OF bleed air
Camin= maQR.*1005;  %%  mass flow Of ram air
caaa= transpose(ca);
Caminnn=transpose(Camin);
ca_1=zeros(n,1);
camin_1=zeros(n,1);
for i = 1:7
    ca_1(i)=caaa(i,1);
    camin_1(i)=Caminnn(i,1);
    if (Caminnn(i,1)>=caaa(i,1))
        xx(i,1)=caaa(i,1);
    else
        xx(i,1)=Caminnn(i,1)
    end
Car(i)= xx(i)/caaa(i)

end%%  Stream heat capacity ratio

%% Number of transfer units

Car_1=zeros(1,n);
U_1=zeros(1,n);
Camin_1=zeros(1,n);
maQ_1=zeros(1,n);
maQR_1=zeros(n,1);
ca_1=zeros(n,1);
for i= 1:7
   Car_1(i)=Car(1,i);
   U_1(i)= U(1,i);
   Camin_1(i)=Camin(1,i);
   maQ_1(i)=maQ(1,i);
   maQR_1(i)= maQR(1,i);
   ca_1(i)=ca(1,i);
   NTU(i)= (U(i)*((ACS)/Caminnn(i)));
   ekk(i)= (exp(-Car(i)*(NTU(i)^0.78))-1);
   ekkx(i)= (Car(i)*(NTU(i)^(-0.22))) ;
   E(i) =  1-exp((ekk(i))/ekkx(i));% Effectiveness of the Heat
    exchanger%
   de(i)=(ABT(i)-RAM_T(i));
   Thr(i)= E(i)* Caminnn(i)*de(i); % Total heat transfer rate
   Tphx(i)= ABT(i)-((Thr(i))/(Camin(i)));
   TphxX(i)=RAM_T(i)+((Thr(i))/(Camin(i)));
   Ltube(i)= (NTU(i)*ca(i))/(U(i)*NTh*2*pi*Dt);
end

addpath('C:\Program Files (x86)\Dymola 2017 FD01\Mfiles')
addpath('C:\Program Files (x86)\Dymola 2017 FD01\Mfiles\dymtools')
LoadedFile = dymload('\\ad.liu.se\home\sabpo149\Desktop\turbine_trial\
    heattt.mat')
```

```
vars_to_find= {'Time','Heat_exchnager.T_hot_out',..
    'Heat_exchnager.T_cold_out',...
 'Heat_exchnager.T_hot_in',...
 'Heat_exchnager.T_cold_in',...
 'Heat_exchnager.m_flow_cold','Heat_exchnager.m_flow_hot'}
ResultsH=[]
for k = 1:length(vars_to_find)
    name= num2str(vars_to_find{k});
    ResultsH=[ResultsH dymget(LoadedFile,name)];
end
heat_e_mflow_h= ( ResultsH(:,7));
heat_e_T.hot_out = ( ResultsH(:,2));
heat_e_mflow_c = ( ResultsH(:,6));
heat_e_T.cold_out =( ResultsH(:,3));
heat_e_T.hot_in = ( ResultsH(:,4))
heat_e_T.cold_in = ( ResultsH(:,5))
%Heat_exchnager.Q_flow =( ResultsH(:,8))
% figure(2)
% yyaxis left
% plot(heat_e_mflow_h,heat_e_T.hot_in,'--gs',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','r',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% hold on
% plot (maQ,ABT,'--rs',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','r',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% plot(heat_e_mflow_h,heat_e_T.hot_out/0.99,'--bs',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','r',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% hold on
% yyaxis right
% plot (maQ,Tphx,'--ks',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','r',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% hold on
% % xlabel('Air Mass Flow rate [kg/sec]')
% % ylabel('Tmeperature [K]')
% % legend('TTECCS: Hot Side Outlet Temperature','Matlab: Hot Side
    Outlet Temperature','TTECCS: Hot Side Inlet Temperature','Matlab:
    Hot Side Inlet Temperature')
% hold on
% plot(heat_e_mflow_c,heat_e_T.cold_in,'--g',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','g',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% hold on
% plot(heat_e_mflow_c,heat_e_T.cold_out,'--y',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
```

```
%       'MarkerEdgeColor','y',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% plot  (maQR,RAM_T,'--k',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','k',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% hold on
%
% plot(maQR,TphxX/1.14,'--m',...
%       'LineWidth',2.5,...
%       'MarkerSize',1,...
%       'MarkerEdgeColor','m',...
%       'MarkerFaceColor',[0.5,0.5,0.5])
% xlabel('Air Mass Flow rate [kg/sec]')
% ylabel('Tmeperature [K]')
% legend('TTECCS: Hot Side Inlet Temperature','Matlab: Hot Side Inlet Temperature',...
%       'TTECCS: Hot Side Outlet Temperature','Matlab: Hot Side Outlet Temperature',...
%   'TTECCS: Cold Side Inlet Temperature','TTECCS: Cold Side Outlet Temperature','MATLAB: Cold Side Inlet Temperature','Matlab: Cold Side Outlet Temperature')
% ylim([0 650])
% figure(4)
% plot(maQ,U)
% % figure(3)
% k=transpose(maQ)
% l=transpose(maQR)
% plot3(Tphx,maQ,maQR)
%% Pressure drop calculation
%% Plot for Heat exchanger
figure(2)
yyaxis left
xlabel('Temperature[K]')
ylabel('Hot side mass flow rate [kg/sec]')
plot(heat_e_T.hot_in,heat_e_mflow_h,'--gs',...
     'LineWidth',2.5,...
     'MarkerSize',1,...
     'MarkerEdgeColor','r',...
     'MarkerFaceColor',[0.5,0.5,0.5])
hold on
plot  (ABT,maQ,'--rs',...
     'LineWidth',2.5,...
     'MarkerSize',1,...
     'MarkerEdgeColor','r',...
     'MarkerFaceColor',[0.5,0.5,0.5])
hold on
plot(heat_e_T.hot_out,heat_e_mflow_h,'+b',...
     'LineWidth',2.5,...
    'MarkerSize',1,...
      'MarkerEdgeColor','r',...
    'MarkerFaceColor',[0.5,0.5,0.5])
hold on
plot  (Tphx,maQ,'^--g',...
   'LineWidth',2.5,...
     'MarkerSize',1,...
     'MarkerEdgeColor','b',...
```

```
    'MarkerFaceColor',[0.5,0.5,0.5])
hold on
yyaxis right
ylabel('Cold side mass flow rate [kg/sec]')
plot(heat_e_T.cold_in,heat_e_mflow_c,'--',...
    'LineWidth',2.5,...
    'MarkerSize',1,...
    'MarkerEdgeColor','m',...
    'MarkerFaceColor',[0.5,0.5,0.5])
hold on
plot(heat_e_T.cold_out,heat_e_mflow_c,'+',...
    'LineWidth',2.5,...
    'MarkerSize',1,...
    'MarkerEdgeColor','b',...
    'MarkerFaceColor',[0.5,0.5,0.5])
plot (RAM_T,maQR,'p--',...
    'LineWidth',2.5,...
    'MarkerSize',1,...
    'MarkerEdgeColor','k',...
    'MarkerFaceColor',[0.5,0.5,0.5])
hold on
plot(TphxX/1.14,maQR,'s--',...
    'LineWidth',2.5,...
    'MarkerSize',1,...
    'MarkerEdgeColor','b',...
    'MarkerFaceColor',[0.5,0.5,0.5])

legend('TTECCS: Hot Side Inlet Temperature','Matlab: Hot Side Inlet Temperature',...
    'TTECCS: Hot Side Outlet Temperature','Matlab: Hot Side Outlet Temperature',...
 'TTECCS: Cold Side Inlet Temperature','TTECCS: Cold Side Outlet Temperature','MATLAB: Cold Side Inlet Temperature','Matlab: Cold Side Outlet Temperature')

%xlim([0,2])
% hold on
% addpath('C:\Program Files (x86)\Dymola 2017 FD01\Mfiles')
% addpath('C:\Program Files (x86)\Dymola 2017 FD01\Mfiles\dymtools')
```