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Environmental Control System Modeling for Configuration Selection for a Light Transport Aircraft

Mr. Rahul Mohan.P[1]
M-Tech, Thermal Power Engg
The Oxford College of Engg
Bengaluru, India
rahulmhnp@gmail.com

Mr. Vinay C.A[2]
Scientist, C-CADD
CSIR-NAL
Bengaluru, India
vinay.ca@nal.res.in

Mr. M L Shankar[2]
Sr. Scientist, C-CADD
CSIR-NAL
Bengaluru, India
mleelashankar@nal.res.in

Mr. Satish D.G[3]
Asst. Professor, Dept. of Mechanical Engineering
The Oxford College of Engineering
Bengaluru, India
satishgovindaswamy@gmail.com

Mr. Shivaprasada K V[4]
Application Engineer
CoreEL Technologies
Bengaluru, India
shivaprasada.kv@coreel.com

ABSTRACT
The work focuses on configuration selection and modeling of Environmental Control System (ECS). The main configuration of an ECS system consists of two heat exchangers, compressor-turbine coupled in a single shaft, condenser and high pressure water separator. The heat exchanger, compressor and turbine are selected as per requirements and the bleed mass flow available from the engine. A system network is created using Flowmaster commercial software and the simulation of ECS is carried out. The obtained results are tabled and the cooling capacity of the pack is calculated from the obtained results under steady state conditions. The cooling capacity of the pack is compared with the provided heat loads under different flight conditions.

Keywords
Aircraft, ECS, Flowmaster, Bootstrap System.

Nomenclature

T_c - Cabin Temperature, ^{o}K

T_p - Pack Outlet Temperature, ^{o}K

T_r - Ram Air Temperature, ^{o}K

P - Pressure at corresponding nodes, bar

$\dot{m}_b$ - Bleed Air Mass Flow Rate, Kg/s

$\dot{m}_r$ - Ram Air Mass Flow Rate, Kg/s

C_p - Specific Heat at Constant Pressure, KJ/Kg-^{o}K

ε - Effectiveness of Heat Exchanger

η - Efficiency

W_c - Actual Work Done by Compressor, KW

W_t - Actual Work Done by Turbine, KW

Subscripts

b - Bleed Air

r - Ram Air

t - Turbine

c - Compressor

i - Isentropic

phx - Primary Heat Exchanger

shx - Secondary Heat Exchanger

con - Condenser

rc - Recirculated Air

Abbreviations

ECS - Environmental Control System

ACM - Air Cycle Machine

COP - Coefficient of Performance

M - Mach Number

TCV - Temperature Control Valve

Comp - Component

1. INTRODUCTION
Environmental Control System (ECS) in aircraft helps to maintain adequate ventilation, pressure, temperature and humidity inside aircraft, which is very important for human comfort and survival inside the aircraft. The main function of the ECS is to maintain adequate temperature and pressure, humidity inside cabin. The supplied air should be sterile and free from dust and contaminants [1]. The ECS also has functions like windshield defog, anti-ice/de-ice, and other pneumatic demands. [2]

A conventional ECS which is installed in most of the aircrafts today operate on hot bleed air from the engines. The outside air is compressed in the engine, cooled in the Air Cycle Machine (ACM) and mixed with equal amount of recirculated air from the cabin and supplied to the cabin. Approximately 0.01 m^3/s of air per passenger is to be provided to the cabin as a minimum requirement. [2] ECS should be able to maintain cabin temperature in between 15^{o}C to 30^{o}C.

A two wheel bootstrap system configuration has two heat exchanger, compressor, turbine, condenser and high pressure water extractor. The hot bleed air from the two engines is passed through primary heat exchanger where hot air is cooled using cold ram air, after passing through primary heat exchanger the bleed air is compressed inside a compressor to increase its pressure further, the temperature is also increased in this process. The hot air from compressor outlet is cooled using secondary heat exchanger. This cool air is passed through condenser and high pressure water separator where the air is cooled to dew point temperature using the cold turbine exit air. The condensed water is extracted using high pressure water separator in order to reduce its specific humidity. The high pressure air undergoes isentropic expansion inside the turbine, which reduces temperature and pressure. The work done by the compressed air inside turbine is transferred to the compressor by a shaft which is coupled between turbine and compressor. The air from the turbine exit is further heated in the condenser, then the cold air is mixed with the unconditioned hot bleed air in the mixing chamber coming from the pipe routing through pilot operated a pneumatically actuated, torque motor controlled butterfly type temperature control valve (TCV). This air is mixed with cabin recirculated air in a mixing unit and is supplied to the cabin using cabin air distribution system. Two wheel bootstrap systems have certain thermodynamic advantages over three wheel system. It has higher coefficient of performance (COP), less weight than three wheel system. [2]

The organization of the paper is as follows: In Section 2, a two wheel bootstrap system configuration is described, Section 3 component selection procedure is explained. Section 4, the system simulation model developed using Flowmaster is described. Section 5, the results obtained from the simulation is tabled and the calculated pack cooling capacity is compared with provided heat loads.

2. SYSTEM DESCRIPTION

2.1 Introduction

The main components of a two wheel bootstrap system are heat exchangers, compressor, turbine, condenser and high pressure water separator. Fig 1 shows a simplified network which includes only main components.

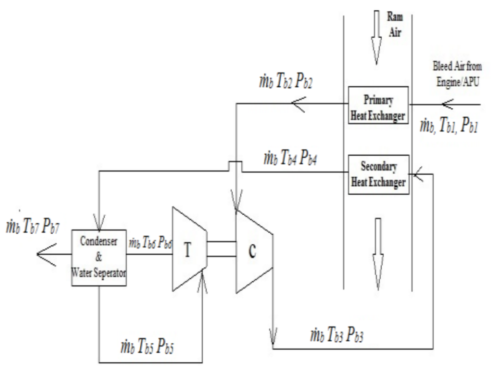

Fig 1: Two Wheel Bootstrap System

2.2 Heat Exchangers

There are two heat exchangers, primary and secondary. The hot bleed air is cooled by ram air using heat exchangers.

The heat transferred from the hot bleed air can be expressed as; [1]

$$Q_{phx} = \dot{m}_b C_{pb} \Delta T_b = \dot{m}_{r1} C_{pr} \Delta T_r \qquad (1)$$

C_{pb} depends on temperature and should be taken as the average of the temperatures, and can't be cancelled out in the equation above.

The effectiveness of the primary heat exchangers can be expressed as; [1]

$$\varepsilon_{phx} = \frac{T_{b1} - T_{b2}}{T_{b1} - T_{r1}} \qquad (2)$$

Assuming that the T_{r1} the ram air temperature for primary heat exchanger.

The effectiveness of the secondary heat exchanger can be expressed as;

$$\varepsilon_{shx} = \frac{T_{b3} - T_{b4}}{T_{b3} - T_{r2}} \qquad (3)$$

Assuming that the T_{r2} the ram air temperature for primary heat exchanger.

2.3 Compressor

The performance of the compressor can be found out by these correlations.

The temperature after isentropic compression inside the compressor is given by; [1]

$$\frac{T_{b3i}}{T_{b2}} = \left(\frac{P_{b3}}{P_{b2}}\right)^{\left(\frac{k-1}{k}\right)} \qquad (4)$$

Efficiency of the compressor is given by; [1]

$$\eta_c = \frac{T_{b3i} - T_{b2}}{T_{b3} - T_{b2}} \qquad (5)$$

The actual work done is; [1]

$$W_c = \dot{m}_b C_{pb} (T_{b3} - T_{b2}) \qquad (6)$$

$$W_c = \frac{\dot{m}_b C_{pb} T_{b2}}{\eta_c} \left[\left(\frac{P_{b3}}{P_{b2}}\right)^{\left(\frac{k-1}{k}\right)} - 1 \right] \qquad (7)$$

2.4 Turbine

The performance of the turbine can be found out by these correlations. [1]

$$\frac{T_{b6i}}{T_{b5}} = \frac{P_{b6}}{P_{b5}}^{\left(\frac{k-1}{k}\right)} \qquad (8)$$

The efficiency of the turbine is given by; [1]

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$$\eta_t = \frac{T_{b5} - T_{b6}}{T_{b5} - T_{b6i}} \tag{9}$$

The turbine work is given by; [1]

$$W_t = \dot{m}_b C_{pb} (T_{b5} - T_{b6}) \tag{10}$$

$$= \dot{m}_b C_{pb} T_{b5} \left[1 - \left(\frac{P_{b6}}{P_{b5}} \right)^{\frac{k-1}{k}} \right] \eta_t \tag{11}$$

The cooling capacity of the pack can be calculated using; [1]

$$Q_{pack} = \dot{m}_b C_{pb} (T_{rc} - T_p) \tag{12}$$

2.5 Condenser

$$Q_{con} = \dot{m}_b C_{pb} (T_{b4} - T_{b5}) \tag{13}$$

$$= \dot{m}_b C_{pb} (T_{b7} - T_{b6})$$

C_{pb} depends on temperature and should be taken as the average of the temperatures, and can't be cancelled out in the equation above.

3. SELECTION OF COMPONENTS

A basic selection procedure is adapted to size or select the component for modeling and simulation needs. A precise calculations and selection to be made under detailed design of the ECS.

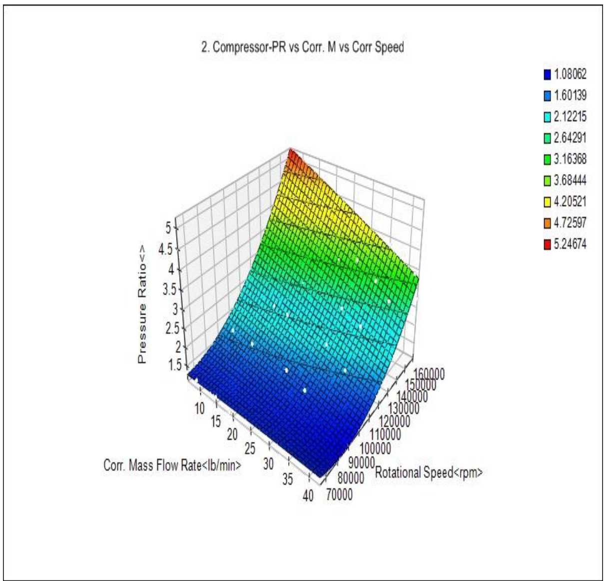
3.1 Heat Exchangers

Rating of both primary and secondary heat exchanger has been supplied hence heat transfer area and effectiveness for both heat exchangers are used for simulation purpose from the supplied data.

3.2 Compressor

As per the bleed mass flow available from the two engines, a centrifugal compressor is selected from Honeywell Garrett [7] for the simulation. The compressor is so selected from the performance curve provided by the manufacture. Operating conditions are taken as selection parameter and not the efficiency curve. An accurate selection should be made from available compressors after comparing simulation results.

Fig 2: Compressor – Pressure Ratio vs Corr. Mass Flow Rate vs Corr. Speed



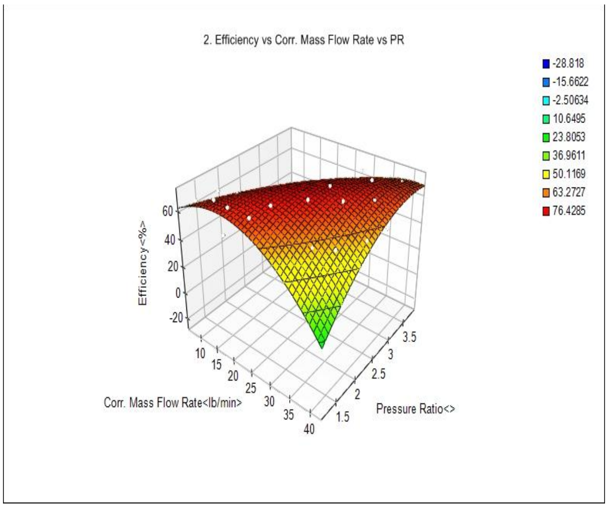


Fig 3: Compressor – Efficiency vs Corr. Mass Flow Rate vs Pressure Ratio

The above fig 2, fig 3 is a Flowmaster generated performance surfaces of the selected compressor which is a transformation of the performance curves provided by manufacture. These surfaces are used in simulation for determining the pressure ratio, efficiency under given conditions.

3.3 Turbine

Turbine specifications are selected from reference test data which was available under similar working conditions and the turbine performance curve is generated using Flowmaster by inputting available test data for various flight conditions. Fig 4 shows a Flowmaster generated performance curve.

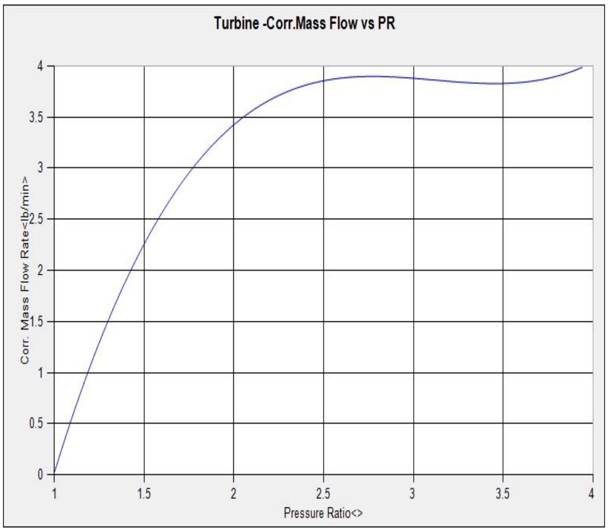


Fig 4: Turbine – Corr. Mass Flow Rate vs Pressure Ratio

4. SYSTEM SIMULATION MODEL

Flowmaster is 1D simulation software which can be used efficiently for system level analysis. Flowmaster gives set of pre-defined components for valves, heat exchangers, compressors, turbines and many other components which are used in aircraft ECS. ECS network is made from these components. The inputs for these components are pre defined boundary conditions, specific inputs for components are arrived from section 3 and also from set of available data within Flowmaster A steady state simulation is used in this work and fig 5 shows the modeled network.

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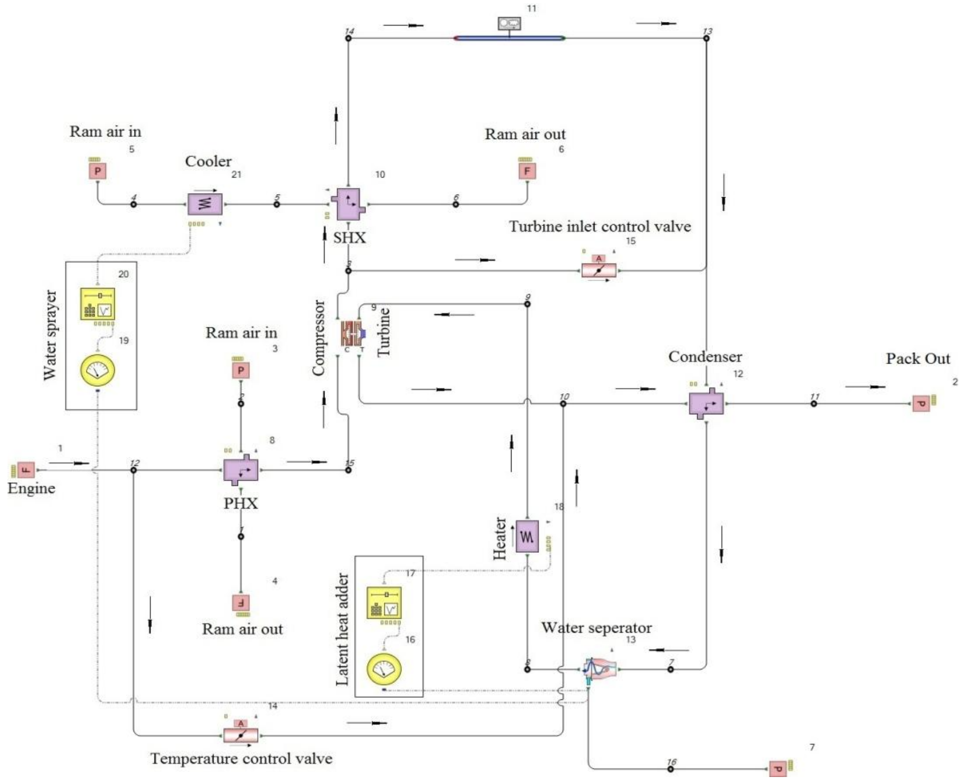

Fig 5: System Simulation Model

The arrow indicated in fig 5 marks the bleed air flow direction in ECS. Flowmaster does iterative calculations to attain steady state from the given inputs. Flow from engine is represented as flow source. The hot bleed air from engine (comp-1) is passed to primary heat exchanger (a thermal heat exchanger component is used for simulation of both primary and secondary heat exchanger, comp-8,comp-10 respectively), where hot air is cooled by ram air flow (ram air flow is simulated using two sources mass flow rate –comp 4 and pressure,comp-3). The ram air flows from pressure source (3) to flow source (4). The heat exchanger outputs are calculated from the input effectiveness. The cooled air then moves to compressor where it gets compressed. Flowmaster provides a single set component of air cycle machine (comp-9) which contains both compressor and turbine. The turbine calculates power and torque and gives a signal input to compressor, compressor in turn uses this signal and returns speed in rpm to turbine, and the net result will be that the turbine and compressor will rotate at same speed [5]. The final output pressure and efficiency, from compressor is calculated from the performance surfaces for the particular compressor, in conjunction with inputs from turbine. The compressed air from compressor is cooled inside secondary heat exchanger. Simultaneously water collected through water separator is sprayed in to ram air duct using a water spray nozzle, hence there will be a reduction in ram air temperature due to vaporization of water which causes more cooling of bleed air in secondary heat exchanger. Gauge and controller (comp-19 and 20) together forms a water sprayer. The water separator (comp-13) will give a logical input to the gauge (comp-19) regarding the amount of water separated from bleed air. A customized c# code is used by gauge to calculate the reduction in temperature of ram air due to the sprayed water. The reduction in temperature is due to latent heat absorbed from ram air by the sprayed water. The code calculates the latent heat absorbed by the sprayed water from the ram air and the final temperature of ram air is arrived from the conservation of energy equation. A cooler (comp-21) is used to account latent heat absorption in the flow. The gauge and controller give logical input regarding the reduction in temperature to the cooler. The cooler in turn reduces the temperature of the ram air with respect to received inputs. Comp 5 and 6 shows the ram air flow through secondary heat exchanger. Now the cool air from secondary heat exchanger passes through condenser (comp-12), where it is further cooled by the cold air from turbine, so that the net result will be the condensing of water vapor in condenser, since the temperature of bleed air will be cooled to dew point temperature. The condensation of water can be avoided by varying the bleed air bypass through valves (comp-14, 15). The water separator extracts free water from air there by reducing the specific humidity of the air. The efficiency of the water separator can be set as per requirement. Similarly the latent heat released in the condenser due to condensation of water and the increase in temperature of the bleed air due to condensation is arrived from the same set of c# codes which is used to simulate water sprayer with simple modifications. The assumption made in condenser simulation is that latent heat released by the water vapor due to condensation is not conducted to air flowing from condenser to cabin and the entire latent heat is carried away by the same air which passes from condenser to water separator. A set of gauge, controller and a heater (comp -16, 17, 18) is used to add latent heat to bleed air. Further the air is expanded inside turbine, and is cooled to sub zero temperature. The turbine uses its own set of performance curve and input efficiency to arrive output parameters. The cold air then flows through condenser and to exit. A temperature control valve (comp-14) is added which ducts engine hot air to turbine exit, in order to control bleed air temperature to the cabin. Also turbine inlet control valve (comp-15) is added to control turbine inlet temperature to avoid icing inside turbine casing. This will bypass hot air from compressor excluding the secondary heat exchanger cooling.

5. RESULTS

The simulation results for 10 flight conditions are provided with ECS input condition. In Table-1 the pack outlet temperature from simulation is presented with input bleed air temperature.

Table 1. Simulation Results of ECS Pack Outlet Air Temperature

SI NO	Flight Cases	Input Temp °C	Simulation Results °C
1	1×10^4 Ft Climb M: 0.44	180.4	-14.12
2	2.5×10^4 Ft Climb M: 0.47	156.7	40.9
3	1×10^4 Ft Cruise M: 0.3	150.3	-16.27
4	1×10^4 Ft Cruise M: 0.43	180.4	-16.2
5	2×10^4 Ft Cruise M: 0.46	167	15.78
6	2.5×10^4 Ft Cruise M: 0.34	140.7	67.25
7	2.5×10^4 Ft Cruise M: 0.44	155.5	43.02
8	0 Ft Descent M: 0.2	168.7	-16.54
9	1×10^4 Ft Descent M: 0.24	169.7	-3.15
10	2.5×10^4 Ft Descent M: 0.33	179.6	67.4

Table 2. Comparison of Heat Load with Cooling Capacity

SI No	Flight Cases	Heat Load (Kw)	Cooling Capacity of Pack (Kw)
1	1×10^4 Ft Climb M: 0.44	4.6	4.69
2	2.5×10^4 Ft Climb M: 0.47	-0.988	-0.985
3	1×10^4 Ft Cruise M: 0.3	3.27	3.4
4	1×10^4 Ft Cruise M: 0.43	4.72	4.83
5	2×10^4 Ft Cruise M: 0.46	0.885	1.01
6	2.5×10^4 Ft Cruise M: 0.34	-1.91	-2.08
7	2.5×10^4 Ft Cruise M: 0.44	-1.21	-1.23
8	0 Ft Descent M: 0.2	4.48	5.12
9	1×10^4 Ft Descent M: 0.24	2.51	2.67
10	2.5×10^4 Ft Descent M: 0.33	-1.98	-1.99

Table 2 shows OEM provided heat load with cooling capacity of pack. Under optimum condition the cooling or heating capacity should match with thermal load.

The cooling capacity of the pack is calculated from the equation no (12), $\dot{m}_b$ in equation no (12) is the mass flow rate of cold air from ECS pack which is mixed with equal amount of recirculated air. The recirculated air temperature T_{rc} will be slightly above or below compared to the mean cabin temperature and it depends on the heat load, work done by recirculated fan, conduction through ducts etc. The pack outlet temperature T_p in equation (12) is obtained from simulation (refer Table 1). In this paper temperature rise for recirculated air compared to mean cabin temperature is assumed on the basis of available ECS test data from similar class of aircrafts.

The above results show that the selected configuration is able to meet the given heat loads for the critical flight cases. Also the ECS will be able to maintain cabin temperature between 15°C to 30°C since pack cooling capacity converges to aircraft heat loads which have been calculated under assumed mean cabin temperature, ranges between 15°C to 30°C.

6. CONCLUSION

In this paper a simplified two wheel bootstrap system configuration is modeled and simulated using Flowmaster, for a 14 seated light transport aircraft. Analysis of system is carried out and the important results are listed, also heat load is compared with pack cooling capacity. Basic selection of components has been done whose parameters are used to model and simulate the simplified ECS configuration.

7. ACKNOWLEDGMENT

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8. REFERENCE

[1] A.P.P Santos, C R Andrade*, E.L.Zaparoli, A Thermodynamic Study of Air Cycle Machine for Aeronautical Applications, International Journal of Thermodynamics (IJOT)

[2] João Batista do Porto Neves Júnior, Cláudia Regina de Andrade, Edson Luiz Zaparoli, Numerical Analysys of Typical Aircraft Air – Conditioning Air Cycle Machines, 20th International Congress of Mechanical Engineering.

[3] Y. Tu[1], G.P Lin[2], Dynamic Simulation of Humid Air Environmental Control System, 40th International Conference on Environmental Systems.

[4] Computer Simulation of an Aircraft Environmental Control System, Shayne Ziegler, Mentor Graphics.

[5] Flowmaster Application Specific Guide: Aircraft Environmental Control Systems-By: Doug Kolak

[6] https://www.turbobygarrett.com