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Aircraft Emergency Environmental Control System Modeling, Configuration Design & Analysis

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ABSTRACT
In a commercial aircraft, cabin ventilation is normally through Environmental Control System. Most often, in all the large civil transportation aircrafts, two or three air-conditioning packs are present for the safety purpose. But in some light transport aircrafts, due to various limitations, only one air conditioning pack is present and so there is a need of an emergency system in case of the pack failure. This emergency system operates only when the normal Environmental Control System is failed.The work focuses on modeling, configuration design and analysis of emergency Environmental Control System for a light transport aircraft. The configuration consists of mainly two heat exchangers and a pressure reducing and shut off valve. The rating of heat exchanger is based on the application and the other components are selected as per requirements and the bleed air mass flow available from the engine. The modeling & simulation of emergency system is carried out using commercial software Flowmaster and the results are compared and presented.

Keywords
ECS, Aircraft Heat Loads, Cooling Capacity, Flowmaster, Boot strap system, Heat exchanger.

Nomenclature

Q	- Heat Transferred(KW)
U	- Overall Heat Transfer Coefficient(W/m^{2}K)
$\dot{m}_b$	- 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/KgK)
ε	- Effectiveness of Heat Exchanger
m_{ff}	- mass flow rate through plate heat exchanger(Kg/s)
s	- Fin spacing (m)
b	- Plate thickness (m)
A_f	- Flow area (m^2)
A_{ff}	- Free Flow Area(m^2)
A_1	-Frontal area (m^2)
A_s	- Heat transfer area (m^2)
A_f	- Fin area (m^2)
K_w	- Conductivity (W/mK)
Deq	- Equivalent diameter(m)
σ	- Frontal area ratio
w	- Width (m)
n	- Number of layers/plates
A	-Area between plates (m^2)
G	-Core mass velocity (Kg/sm^2)
μ	-Viscosity (Ns/m^2)
ρ	-Density (kg/m^3)
h	- Heat transfer coefficient(W/m^{2}K)
Pr	- Prandtl number
Re	- Reynolds Number
η_f	- Fin efficiency (%)
N_o	- Overall efficiency(%)
j	- Colburn Factor
f	- Friction Factor
T_a	- Ambient temperature(^{0}C)
T_{rc}	- Re-circulated temperature(^{0}C)
T_p	- Pack outlet temperature to the cabin(^{0}C)

Subscripts

b	- Bleed Air
h	-hot side
c	-cold side
r	- Ram Air
$hx1$	- Heat Exchanger 1
$hx2$	- Heat Exchanger 2
rc	- Re-circulated Air

Abbreviations

ECS	- Environmental Control System
ACM	- Air Cycle Machine
LTA	-Light Transport Aircraft
M	- Mach Number
PRSOV	- Pressure reducing & Shut off Valve
HP	-High Pressure
OEM	-Original Equipment Manufacturer

1. INTRODUCTION

Environmental Control System controls the temperature, pressure and airflow into the aircraft pressure vessel which includes the cockpit, cabin and the interior compartments. This helps in providing comfort and protecting the passengers and crew when the aircraft is flying over 10000 feet. The main function of the ECS is to maintain adequate temperature, pressure, and humidity inside the cabin [1]. The ECS also has functions like anti-icing, pressurisation, windshield defog, de-icing and other pneumatic demands.

The most important part of the ECS is its air-conditioning system. ACS conditions the air from the bleed air system and supplies it to the cockpit and cabin. Air conditioning packs are the core components of air conditioning system[2]. The Boot strap air conditioning system is the common choice adopted by the most of the civil aircrafts. The schematic diagram of a simple two wheel boot strap system is shown in Fig 1:

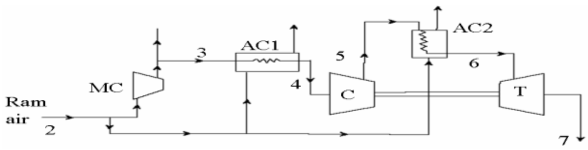

Fig 1: Two Wheel Bootstrap System

A simple two wheel bootstrap system configuration has two heat exchangers & ACM (compressor and a turbine).Due to the ram effect, the ambient air is pressurized to state 2. This air is further compressed to state 3 in the main compressor. This hot bleed air from the engine is passed through primary heat exchanger, where it is cooled to state 4 using ram air. Then the air at state 4 is compressed to state 5 using a compressor. The temperature is also increased during this process. It is then cooled to state 6 by a secondary heat exchanger and finally expands to cabin pressure in the turbine and is supplied to the cabin at low temperature at T7. The condenser and water extractor may also be used to maintain humidity and to cool the air to dew point temperature using the turbine exit cold air.

Generally, there are two or three air-conditioning packs for safety purpose in all the large civil aircrafts. But the situation is different in case of light transport aircrafts with less number of passengers as only one air conditioning pack is been used. The limitations of having an additional pack in these aircraft includes more costs, space requirement, weight etc. So it is not possible to have an additional air-conditioning pack comprising of turbine, compressors, condenser etc which requires more space, more cost & even adds more weight to the system. So there is a large scope in modifying the existing ECS without air cycle machine and can serve the purpose during the emergency situations. This emergency system operates only when the normal ECS pack is failed.

The description of the work carried out is presented: In section 2, emergency ECS configuration is described. In section 3, selection of various components for the configuration is explained which includes the design of heat exchanger using Magahanic Correlations [4]. In Section 4, the system simulation model developed using Flowmaster is described. In Section 5, the results obtained from the simulation are summarised and analysed.

2. SYSTEM DESCRIPTION

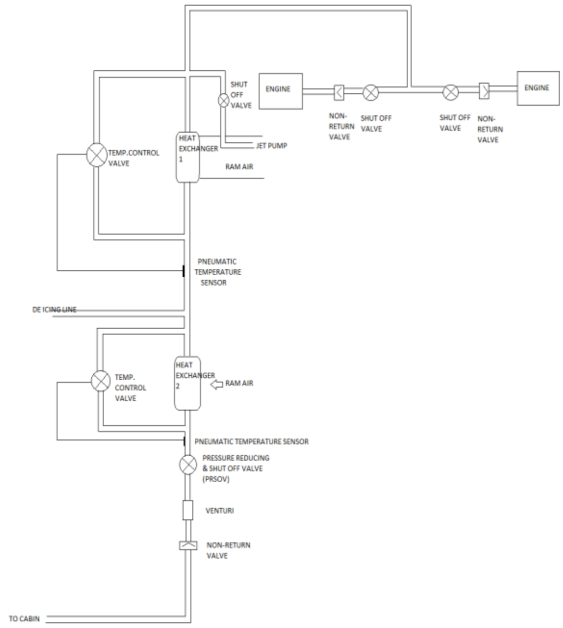

Fig 2: Configuration of Emergency ECS of LTA.

2.1 Introduction

In the rare event of normal ECS pack failure, an emergency back-up system is provided for the cooling and pressurisation of the cabin. The main components are heat exchangers, PRSOV ,temperature control valve and shut off valve.

2.2 Operation

From the alternative HP bleed port of the engine, the emergency supply is taken. The emergency air supply is controlled by a Non- return & shut off valves fitted for each two engines. The Shut-Off Valve, which will be mounted on the engine firewall, is opened via an electrical signal. The Non-Return Valve is used to ensure that bleed air is not cross bled from one engine to the other. The air supply after combination from both engines enters the heat exchanger 1 where the temperature reduction takes place by ram air cooling. Around heat exchanger, a Temperature Control Valve (controlled by a Pneumatic Temperature Sensor) is fitted to bypass the bleed air. This ensures that the air supply from the heat exchanger does not become too cold. From heat exchanger 1, some amount of the bleed air goes to the de-icing line & serves the de-icing purposes in aircraft. The remaining air enters the heat exchanger 2 where the temperature is again reduced by using ram air. Temperature control valve ensures that the air is not cooled to an undesired level. The air is then supplied through PRSOV and venturi, which control total emergency air flow in to the cabin. A jet pump induces coolant flow through the heat exchanger 1, while the aircraft requires de- ice flow but is not in flight.

2.3 Heat Exchangers[1]

The main component of the emergency ECS is heat exchanger. Two heat exchangers are used in the emergency ECS, one after the de-icing line & the other before the de-icing line as shown in Fig: 2. Using heat exchangers, the hot bleed air is cooled by ram air.

The heat transferred from the cold ram and hot bleed air can be equated as;

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$$Q_{hx} = \dot{m}_b C_{pb} \Delta T_b = \dot{m}_r C_{pr} \Delta T_r \qquad (1)$$

C_{pb} and C_{pr} are the specific heats of bleed and ram air respectively, depends on temperature and can't be cancelled out from the equation above.

The effectiveness of heat exchanger 1 (Assuming C_{min} is equal to C_{pb}) is expressed as [1];

$$\varepsilon_{hx1} = \frac{T_{b1} - T_{b2}}{T_{b1} - T_{r1}} \qquad (2)$$

The effectiveness of heat exchanger 2 is expressed as;

$$\varepsilon_{hx2} = \frac{T_{b3} - T_{b4}}{T_{b3} - T_{r2}} \qquad (3)$$

Where

T_{b1} = bleed air temperature entering heat exchanger 1
T_{b2} = bleed air temperature leaving heat exchanger 1
T_{b3} = bleed air temperature entering heat exchanger 2
T_{b4} = bleed air temperature leaving heat exchanger 2
T_{r1} = ram air temperature entering heat exchanger 1
T_{r2} = ram air temperature entering heat exchanger 2

Assuming that the T_{r1} is equal to T_{r2}

3. SELECTION OF COMPONENTS

3.1 Introduction

The 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 the detailed design of the ECS.

3.2 Design procedure of heat exchanger[4]

The heat exchanger selected is a cross flow, single pass plate heat exchanger. All the nomenclatures and subscripts used are given in page 1.

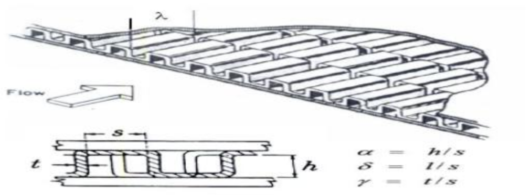

Fig 3: Geometry of a Typical Offset Strip Fin Surface[4]

Spacing of fin(s) $= \dfrac{1}{f} - t$ (4)

Where

f is frequency of the fin

t is thickness of the fin

Plate thickness (b) $= h + t$ (5)

Where h is height of fin

Flow area (A_{fl}) $= (s - t)h$ (6)

Frontal area (A_1) $= (h + t)(s + t)$ (7)

Heat transfer area (A_s) $= 2hl + 2sl + 2ht$ (8)

Where l is the fin length

Fin area (A_f) $= 2hl + 2ht$ (9)

Equivalent Diameter (D_{eq}) $= \dfrac{2lh(s - t)}{ls + hl + ht}$ (10)

Fin area/ heat transfer area $= \dfrac{A_f}{A_s}$ (11)

Frontal area ratio (σ) $= \dfrac{A_{ff}}{A}$ (12)

Assume: at average temperature for both cold and hot side - inlet and outlet temperatures, pressure at inlet, pressure drop allowable & density.

Width (w) - assume for cold & hot sides

No: of layers(plates)(n) - assume for cold side and hot side

Area between plates(A) $= wbn$ (13)

Free flow area (A_{ff}) $= A\sigma$ (14)

Bulk temperature

$$= \frac{\text{Inlet Temperature} + \text{Outlet Temperature}}{2} \qquad (15)$$

Average wall temperature

$$= \frac{Bulk\ temperature_{hot} + Bulk\ temperature_{cold}}{2} \qquad (16)$$

Mean film temperature

$$= \frac{Bulk\ Temperature + Wall\ temperature}{2} \qquad (17)$$

At Mean film temperature, the properties like prandl number(Pr), viscosity,& specific heat are to be calculated (for both hot & cold side).

Core Mass Velocity (G) $= \dfrac{m_{ff}}{A_{ff}}$ (18)

Reynolds's No (Re) $= \dfrac{GD}{\mu}$ (19)

Friction factor (f)=

$$0.32 Re^{-0.287} \alpha^{0.221} \delta^{-0.183} \nu^{-0.023} \qquad (20)$$

where

$$\alpha = \frac{h}{s},\ \delta = \frac{l}{s},\ \nu = \frac{t}{s}$$

Colburn factor (j)=

$$0.18\, Re^{-0.42} \alpha^{0.288} \delta^{-0.184} \nu^{-0.05} \qquad (21)$$

Pressure drop=

$$\frac{fG^2}{2\rho D_{eq}} \tag{22}$$

Heat transfer coefficient (h)=

$$jC_pG/Pr^{-\frac{2}{3}} \tag{23}$$

Fin efficiency (η_f) = $$\frac{\tanh(ml)}{ml} \tag{24}$$

where;

$$M=\sqrt{\left[\frac{2h}{K_f t}\right]},\ \ ml_f=\frac{Mb}{2}$$

Overall efficiency (N_o)=

$$1-\left(\frac{A_f}{A_s}\right)\left(1-\eta_f\right) \tag{25}$$

Total area/Separating area (A_o/A_w)=

$$\frac{(1-ft)}{1-\left(\frac{A_f}{A_s}\right)} \tag{26}$$

Overall thermal resistance ($1/U_o$)=

$$\frac{n_c w_c}{n_h w_h N_{oh} h_h}+\frac{aA_o}{K_w A_w}+\frac{1}{N_{oc} h_c} \tag{27}$$

Overall heat transfer coefficient (U_o)=

$$\frac{1}{\left[\frac{n_c w_c}{n_h w_h N_{oh} h_h}+\frac{aA_o}{K_w A_w}+\frac{1}{N_{oc} h_c}\right]} \tag{28}$$

NTU[4] = $\frac{U_o A}{C_{min}}$

[Where $C_h = \dot{m}_h C_{ph}$, (29)

$C_c = \dot{m}_c C_{pc}$, $C = \frac{C_{min}}{C_{max}}$]

Required heat transfer area per length = $\frac{4A_{ff}}{D_{eq}}$

Required length of heat exchanger;

$$\frac{required\ heat\ transfer\ area}{required\ heat\ transfer\ area\ per\ length} \tag{30}$$

Effectiveness of cross flow heat exchanger [8]=

1-exp{(exp(-NTU*C*NTU$^{-0.22}$)-1)/(C*NTU$^{-0.22}$)} (31)

The above method is used for rating of both the heat exchangers used in the emergency system.

3.3 Shut off valve

The shut off valve selected is a pneumatically operated, nominal 1.5 inch diameter with stainless steel construction. The selection of valve position is provided by a solenoid. The valve shall be capable of being selected closed or open with any upstream pressure (within the range 8 psig to 109.5 psig).

3.4 Non-return valve

The valve selected is a double flap insert type non-return valve that is suitable`for installation in a 1.5 inch diameter duct.

3.5 Pressure reducing & Shut off Valve(PRSOV)

The valve is a solenoid operated, nominal 1.5 inch diameter, single headed valve with stainless steel construction. The valve shall be capable of operating over an upstream pressure range of 25 psig to 109.5psig. When open the valve, the valve is to regulate the downstream pressure to 12 ± 3 psig.

3.6 Temperature control valve

The valve selected is a pneumatically actuated valve, nominally 1.3 inch diameter with stainless steel construction. The valve operates in conjunction with pneumatic temperature sensor.

3.7 Jet Pump

This unit is manufactured from stainless steel and is a bifurcated duct fitted with 4 nozzles.

4. SYSTEM SIMULATION MODEL

4.1 Flowmaster V7 Simulation[5] [6]

Flowmaster V7 is an advanced CAE/CFD modeling tool that can be used efficiently for system level analysis. It has set of various pre-defined components used in aircraft ECS such as heat exchangers, valves, turbines, compressors etc The inputs for these components are taken from the set of available data based on material properties, aircraft structure, geometry etc.

The two engines are represented as pressure source as shown in Fig 4: Starting from station 1, the bleed air flow splits into two lines, one enters the main line and the other goes to the anti-icing line(represented as flow source). The state of bleed air after mixing from the two engines is represented by station 2. The inlet condition to the heat exchanger 1 is represented by Station 3 & Station 4 represents the outlet condition of the heat exchanger 1. From station 4, the flow again splits into two, one enters the heat exchanger 2 and the remaining goes to the de-icing line. Station 5 & 6 represents the inlet and outlet condition of the heat exchanger 2. It then enters pressure reducing and shut off valve and outlet condition of the valve is represented by station 7 .Station 8 represents the outlet condition of air after passing through the venturi. Station 9 represents the total emergency flow into the cabin and represented as flow source.

The pressure source in the network represents the the total pressure of the ram air supplied to the two heat exchangers & total pressure of the bleed air from the two engines. The air flow into the de-icing line , anti-icing line and to the cabin I represented by flow sources. Ball valve is used to represent PRSOV, temperature control valve, shut off valve & non-return valve. By varying the valve opening ratio, the required pressure loss for the PRSOV is achieved. The temperature control valve controls the flow by adjusting the valve position. Thermal heat exchanger is used to make account of the two heat exchangers used in the system. Discrete losses represents the loss in venturi and pressure loss due to mixing. Cylindrical gas pipe represents the pipe lines in the network.

The configuration network is made by using the above components. A compressible steady state simulation is used.

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Fig 4: shows the modeled network.. Flowmaster does iterative calculations to attain steady state from the given inputs. [5] [6].The simulation is done by keeping both the temperature control valves closed. The nine different flight conditions are taken and simulation is done.

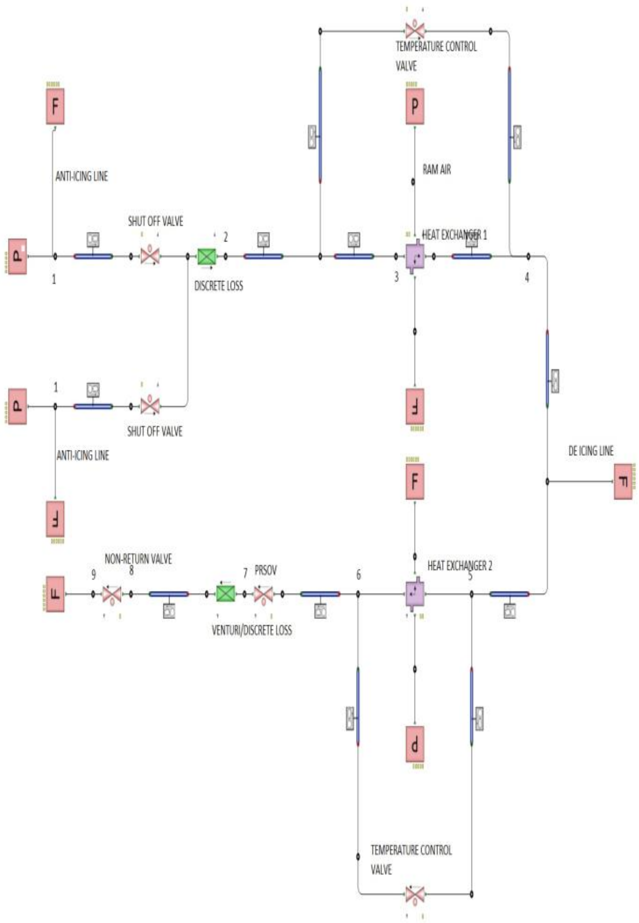

Fig 4: System Simulation Model

5. RESULTS & DISCUSSIONS

5.1 Simulation results

The simulation for the nine different flight conditions is carried out..The simulation results for 20000 ft cruise(T_a=0.38 ^{o}C, M=0.46) is shown below. Table 1 shows the temperature, pressure and mass flow rate variations from station 1 to station 9, where station 1 represents the engine and station 9 represents the flow to the cabin as shown in Fig:4.

Table 1. Simulation results:20000 ft, hot day cruise T_a=0.38^{o}C,M=0.46

Station No:	**Temperature (^{o}C)**	**Pressure (psi)**	**Mass flow (lb/min)**
1	302.7	56.43	9.612
2	302.7	52.67	13.7053
3	302.7	52.39	13.0753
4	87.582	50.2636	13.07
5	87.58	50.26	8.5153
6	24.0931	49.6022	8.5153
7	24.09	18.6646	8.51
8	24.09	15.30	8.51
9	**24.09**	**14.9**	**8.51**

Similarly, the simulation of the remaining eight flight conditions is carried out and pack outlet temperature obtained from simulation is shown in Table 2. The pressure obtained at station 9 for all the flight conditions is around 14 psig which is the desired pressure.

The emergency pack outlet temperature can also be theoretically found out from equation (32) .The effectiveness of the heat exchanger is found out using an estimated thermal characteristic curve of the heat exchangers (not included in this work due to its proprietary nature), then it is substituted in the equation (32) to get the bleed air temperature T_{b4} ,leaving the heat exchanger. Since C_{min} is equal to $C_{pb,}$ we have,

$$\varepsilon_{hx} = \frac{T_{b3} - T_{b4}}{T_{b3} - T_{r1}} \qquad (32)$$

The pack outlet temperature using the above method and from the flowmaster simulation is shown in Table 2 and it can be concluded that simulation and theoretical results are approximately equal.

Table 2. Comparison of simulation and theoretical results

Sl no :	**Flight cases**	**Pack outlet temperature from simulation (^{o}C)**	**Pack outlet temperature using theoretical method (^{o}C)**	**Error (^{o}C)**
1	10000 ft cruise,M:0.3	36.02	36.0	0.02
2	20000 ft cruise,M:0.3	27.90	27.5	0.4
3	20000 ft cruise,M:0.46	24.09	24.1	0.01
4	25000 ft cruise,M:0.34	19.84	19.66	0.18
5	25000 ft cruise,M:0.44	18.64	18.62	0.02
6	0 ft descent,M:0.2	46.86	46.68	0.18
7	10000 ft descent,M:0.24	28.66	29.83	1.17
8	20000 ft descent,M:0.3	9.24	10.15	0.91
9	25000 ft descent,M:0.33	-0.30	-0.2	0.1

The capacity of the system simulated to take on the heat load is known after comparing the cooling capacity and the heat load. The heat load for the different flight conditions were provided by OEM. Table 3 compares the heat load & cooling capacity of emergency pack. The heat load should always be lower than the cooling capacity. The optimum condition meets when the heating or cooling capacity matches with the heat load both in sign & magnitude.

The cooling capacity[7] of the pack can be calculated using;

$$Q_{pack} = \dot{m}_b C_{pb} (T_{rc} - T_p) \qquad (33)$$

Where. T_{rc} is the re-circulated temperature & m_b is the pack outlet mass flow of air to the cabin. It is assumed to be few degrees more or less than the mean cabin temperature and varies according to the flight conditions & heat load. T_p is the emergency pack outlet temperature supplied to the cabin. C_{pb} is the specific heat of the air. Cabin temperature is assumed as 25°C for the 25000 ft and 20000 ft flight conditions. For 0 ft and 10000 ft flight conditions, cabin temperature is taken as 40 °C. This is because minimum temperature that can be attained in the cabin depends on the ram air temperature, as the only source that lowers the temperature in this system is heat exchanger(For 0 ft and 10000 ft flight conditions, temperature of the ram air available is more than 40 °C and 20.19 °C respectively,as per the given flight conditions)

Table 3. Comparison of heat load with cooling capacity

Sl no	Flight Cases	Heat Load (KW)	Cooling Capacity of Pack (KW)
1	10000 Ft Cruise M:0.3	0.81	0.85
2	20000 Ft Cruise M:0.3	0.03	0.06
3	20000 Ft Cruise M:0.46	0.09	0.31
4	25000 Ft Cruise M:0.34	-1.48	0.43
5	25000 Ft Cruise M:0.44	-0.76	0.51
6	0 Ft Descent M:0.2	4.62	0.16
7	10000Ft Descent M:0.24	0.49	1.15
8	20000Ft Descent M:0.3	0.03	0.71
9	25000 Ft Descent M:0.33	-1.87	0.9

The above results shows that the selected configuration for emergency ECS can easily take out the heat load for the above considered flight cases as the cooling capacity is greater than the heat load except 0 ft descent Mach number: 0.2 that have major cooling capacity reduction compared to heat load. This is because of high skin temperature and so the convective heat loads increases in this condition. As this emergency system is used only during emergency and the aircraft will not continue its flight at 0 ft condition, this cooling capacity reduction doesn't make major discomfort for the crew and passengers. It is suggested that the cooling capacity & heat load should match for each flight cases. So in the cases where cooling capacity is very large as compared to the heat load ,the temperature control valve in the system operates and it supplies hot air. The same principle applies when heat load becomes negative, since in those cases we have to supply hot air.

5.2 Conclusion

In this paper, aircraft emergency environmental control system modeling, configuration design and analysis has been carried out.

It is evident from the results that this ECS configuration serves the purpose during emergency conditions. It also serves the de-icing purpose in light transport aircraft. The efficiency of such a system with no air-cycle machine and less number of components will be low as compared to the normal ECS pack, but more research and study can be done in order to make this system efficient and comparable with normal ECS. Also there is a large future scope of work to incorporate the humidity factor in this system, as the humidity effects are not considered in this work.

6. ACKNOWLEDGMENT

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