Heat Load Calculation for the Design of Environmental Control System of a Light Transport Aircraft

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Abstract -- Environmental Control System (ECS) is a generic term used in aircraft industry for maintaining the required air temperature and pressure inside passenger and crew compartment. The real challenge for an ECS is to operate and supply adequate cooling over a wide range of ground and flight conditions in a most reliable and efficient manner. The most important aspect of ECS is to know the cabin heat loads during air cooling or air heating phases. A precise calculation of aircraft heat load would be a long process requiring detailed knowledge of the aircraft structure and of the quantities involved in the mechanism of heat pick up and interchange in the cabin. This paper describes a method that may be applied in calculating the heat load for any aircraft and calculations are shown for a typical light transport aircraft under the conditions that, the cabin altitude is maintained within 0 ft to 8000 ft (2438.4m) for the aircraft altitude of 0 ft to 25000ft (7620m). The system shall be capable of maintaining temperatures within 59°F to 75°F (15°C to 30°C).

Index Terms - Aircraft, Cabin Altitude, Cold air unit, Cooling Capacity, ECS, Heat Load, Heat exchanger

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1 INTRODUCTION

The most important aspect of ECS is to know the cabin heat loads during air cooling or air heating phases. A precise calculation of aircraft heat load would be a long process requiring detailed knowledge of the aircraft structure and of the quantities involved in the mechanism of heat pick up and interchange in the cabin. However, it is possible to make a sufficiently accurate estimate using mean quantities for calculating the heat transfer process providing we know the essential details of the cabin structure such as the transparency areas and the external wall areas and whether or not the aircraft is to be insulated.

NOMENCLATURE

T_s	-Skin temperature (^oK)
T_{amb}	-Ambient temperature (^oK)
γ	-Isentropic factor of air
Q	- Heat Transferred (W)
U	- Overall Heat Transfer Coefficient (W/m^{2}K)
A_{c1}	- Insulated External Wall Area (m^2)
A_{c2}	- Un-Insulated External Wall Area (m^2)
A_{B1}	- Insulated Bulkhead Area (m^2)
A_{B2}	- Un-Insulated Bulkhead Area (m^2)
A_5	- Non-Insulated Projected Area (m^2)
A_6	- Floor Area (m^2)
A10	- Passenger Compartment Window Projected Area(m2)
A11	- Windscreen Window Projected Area (m2)
A12	- Flight Deck Side Window Projected Area (m2)
Acw	- Passenger Compartment Window Total Area (m2)
Aww	- Windscreen Total Area (m2)
Afd	- Flight Deck Side Window Total Area (m2)
Ts	- Skin Temperature (oK)
Tc	- Cabin Temperature (oK)
TB	- Adjacent Bay Temperature (oK)
Tf	- Under Floor Temperature (oK)
TBW	- Non-Insulated Bulkhead Wall Temperature (oK)
Tun	- Non-Insulated Projection Temperature (oK)
HR	- Equivalent Radiation Coefficient (W/m2K)
hi	- Internal Heat Transfer Coefficient (W/m2K)
	- Transmissivity of the material
G	- Solar Radiation Intensity (w/m2)
M	-Mach number
Cp	-Specific Heat of Air (KJ/Kg-K)
b	-Mass flow rate from ECS pack (Kg/s)
Trc	- Re-circulated air temperature from cabin (oK)
Tp	--Air temperature from ECS pack (oK)
QT	- Total Heat Load (KW)
Qc	- Cooling Capacity (KW)
r	- Recovery Factor
tc	- Cabin Temperature (oC)
tamb	- Ambient Temperature (oC)

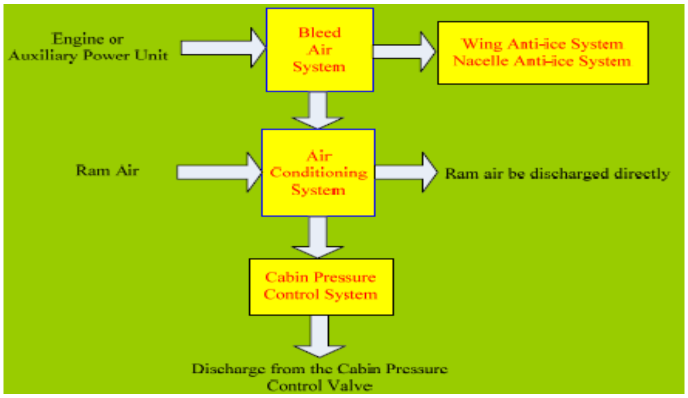

Fig 1 Configuration of a Typical ECS

For example, to predict accurately the heat pick up due to convection one should know the internal airflow over the various surfaces. It is not possible to predict the flow distribution particularly in the case of a small cockpit where the velocity may vary widely throughout. Hence related to internal heat transfer co-efficient to the air mass flow per unit volume of the cabin. ECS system has to be designed by considering the critical heat loads in order to ensure an acceptable temperature level and sufficient air supply in the cabin. Thus the heat load of steady-state heat balance is the necessary input for designing an air conditioning system. The typical configuration of a classic ECS is shown in Fig.1.

2 SYSTEM DESCRIPTION

In the Light Transport Aircraft (LTA), the air conditioning system operates using engines bleed air and supplies controlled conditioned air to the passenger and the crew compartments. Refrigeration is produced by a single bootstrap air cycle system. The schematic arrangement of the air conditioning system is shown in Fig.2.

The temperature control functions are accomplished automatically by an electronic controller in conjunction with an electro-pneumatic Temperature Control Valve. Scheduled maintenance has been minimized by the use of air bearings in the Cold Air Unit (CAU) and high pressure water separation. Re-circulated cabin air is mixed with sub-zero air conditioning pack outlet air to achieve the required cabin conditioning airflow with minimum engine bleed airflow, in order to maintain cabin and crew compartment temperature in the range of 15°C to 30°C up to altitude of 25,000 ft.

2.1 System Operation

With reference to Fig.2 engine bleed air enters the system from either the LP bleed port via a Non-return valve (item 1a & 1b) or the HP bleed port via a Pressure Reducing and Shut-Off valve (item 2a & 2b) depending on the bleed temperatures and pressures. The bleed air then, flows through a Pressure Regulating and Shut-Off valve (item 3a & 3b) and into the system. The bleed air from the two engines is then combined to pass through the Shut-Off valve (item 6) and the flow limiting venturi (item 7) before entering the primary section of the Dual Heat Exchanger (item 10). The bleed air is cooled by passing through the Primary section of the Dual Heat Exchanger and then it enters the compressor section of the Cold Air Unit (item 9) where it is compressed. The heat of the compression is removed in the Dual Heat Exchanger (item 10) where the temperature is reduced to near the ambient air (used for cooling in heat exchanger) temperature. After passing through the high-pressure water separation system condenser / water extractor (item 11), the air enters the turbine section of the Cold Air Unit (CAU) where it expands and gets cooled. The power produced by the turbine in expanding the air is used to drive the compressor. The expansion in the turbine causes a substantial temperature reduction, resulting in sub-zero turbine discharge temperature. When operating on the ground and at low Mach numbers coolant air for the primary/ secondary Dual Heat Exchanger (item 10) is induced by a Ground Cooling (GC) fan (item 18). The GC fan is ON can be used on ground and is switched OFF when the MLG is retracted after getting airborne. During flight and at high Mach numbers, ram air is used. A Non Return valve (item 28) prevents reverse flow of the cooling air. The air from the outlet of the CAU turbine passes through the coolant side of the condenser to be mixed with re-circulated cabin air. The Non Return valve (item 41) prevents flow to the Ground Connector (item 42) and the Non Return valve (item 40) prevents flow to the emergency supply line. If air is supplied from either the ground connector or the emergency supply, the Non Return valve (item 16) will prevent reverse flow to the air conditioning pack. The water drained from the condenser/water extractor (item 11) is sprayed into the Dual Heat Exchanger cooling air inlet through a water spray nozzle (item 17). This reduces the temperature of ram air by evaporation of the water. Conditioned air from the air conditioning pack mixes into re-circulated cabin air in the pressurized area of the aircraft. This air is delivered to both the crew and passenger compartments. The recirculation air does not penetrate the pressure bulkhead. Re-circulated cabin air is added to pack-conditioned air via a filter (item 25) by an electrically driven fan (item 24) allows hot air to bypass the cooling pack to raise the pack outlet temperature when full cooling is not required. This hot air is mixed with pack-conditioned air at the turbine discharge upstream of the condenser. A turbine inlet low limit control valve (item 12) is used to prevent excessively low turbine inlet temperatures on cold days. This prevents icing on the condenser. The condenser also incorporates heated header bars to reduce formation of ice. Hot air supply is taken from the compressor outlet and returned to the air conditioning pack at the primary section outlet of the Dual Heat Exchanger.

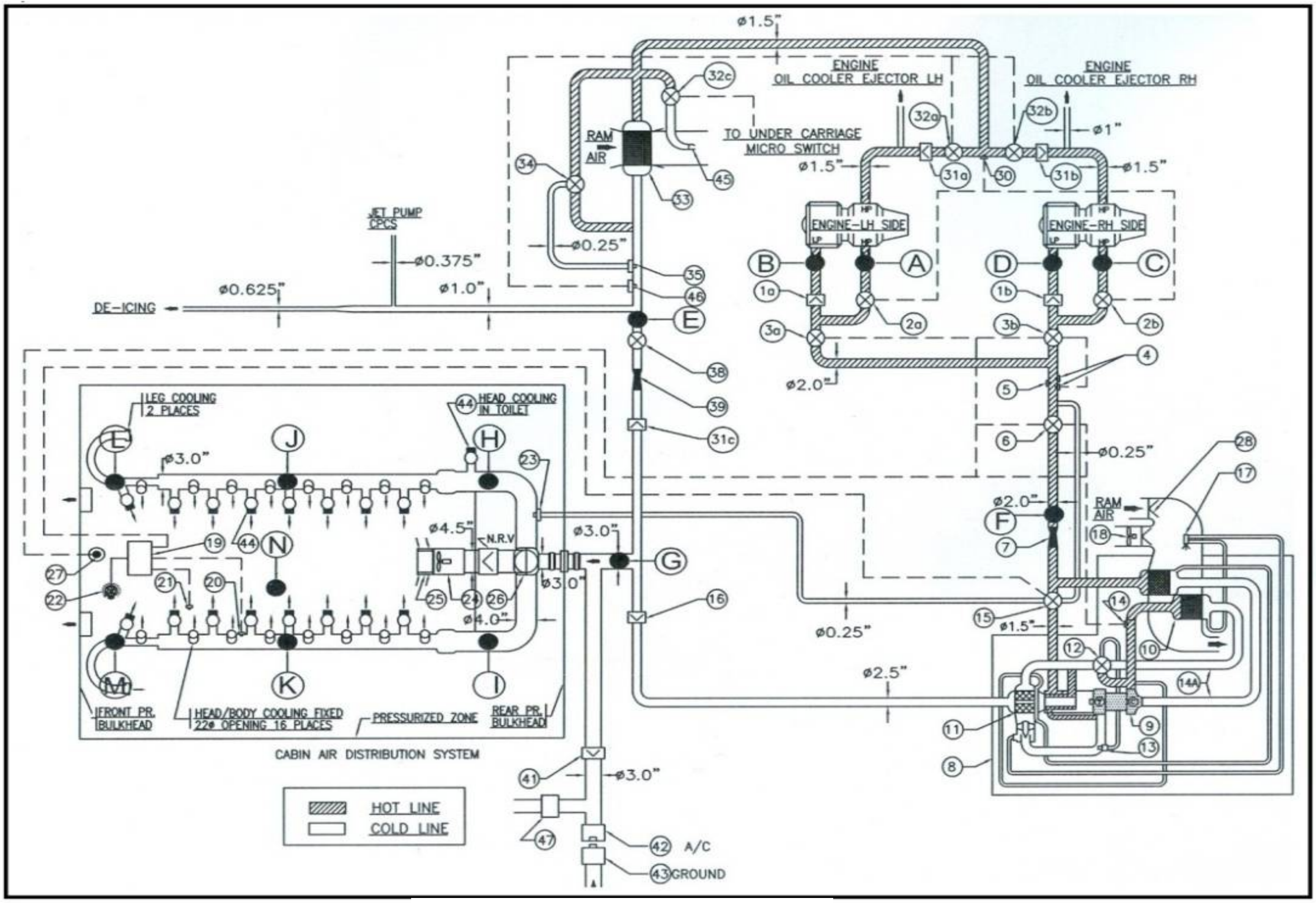

Fig 2 ECS schematic

2.1 Backup Overheat Protection

An overheat protection backup is provided by the Duct Temperature Limiter (item 23) which prevents supply of hot air above 65°C either due to malfunction of the automatic system or inappropriate manual mode system operation. When the temperature of supply air exceeds 65°C the Duct Temperature Limiter opens in response to further temperature increases and actuates the butterfly valve towards the closed position. This control action limits the maximum supply air temperature to 80±5°C.

2.2 Backup Emergency Supply

In an emergency to maintain the pressurization, in the unlikely event of pack failure, is provided. The air supply for this system is taken from the alternative HP bleed port. The emergency air supply is controlled by Shut-Off and Non-Return valves (items 31 & 32) fitted for each engine. The Shut-Off valve is opened by an electrical signal. The Non Return valve is to ensure that air cannot be cross-bled from one engine to the other engine. The air supply after combination from both engines enters the Pre-cooler (item 33) where its temperature is reduced by ram air-cooling. A pneumatic sensor (item 35) fitted around the Pre-cooler enables bypassing engine bleed air on cold days by controlling the temperature control. The air is then supplied via a pressure reducing and shut off valve (item 38) and venture (item 39), which control total flow of emergency air to cabin. On ground, ram air to the pre – cooler (item 33) is initiated by jet pump SOV (item 32) and jet pump (item 45).

2.3 System Protection

The over-temperature switch (item 30) is required to regulate the supply of hot temperature air from the engine. In the event of failure of the over-temperature switch (item 30), two additional over-temperature switches (item 4) are fitted downstream of the Pressure Regulating and Shut-Off Valve (item 3). These additional over temperature switches will signal both engine Pressure Regulating and Shut-Off Valves (item 3) and the Pack Inlet Shut-Off Valve (item 6) to close and illuminate the warning light ECS (item 27). In the case of failure of Pressure Regulating and Shut-Off Valves (item 3), the pack inlet Shut-Off Valve (item 6) will get the signal to close thereby protecting the air conditioning pack from supply of air at overpressure. At the same time the warning light (item 27) will also be illuminated.

3 AIRCRAFT HEAT LOAD

Aircraft heat load can be regarded as heat coming from mainly four aspects, the fuselage wall, the solar radiation, the aircraft occupants and the electronic-electrical equipment [1]. It is easy to describe these sources but difficult to finish a complete and precise calculation because there are so many factors that should be taken into account at the same time. Further, flight altitude and speed also affect the calculation results. Following sections describes the typical method used to estimate the aircraft heating and cooling load in terms of the Light Transport Aircraft (LTA) structural parameters and cabin layout.

3.1 Estimation of Cabin Heat Load

The heating and cooling loads which have to be considered in sizing the environmental control system are:

Convection from External Insulated Wall (Q_1) (W)

$$U_1 A_{c1}(T_s - T_c) \qquad (1)$$

Where;

$$T_s = T_{amb}\left(1 + r\frac{\gamma - 1}{2}M^2\right)$$

r- Recovery factor, γ – Isentropic factor

$$T_s = T_{amb}(1 + 0.18M^2)$$

Where;

r = 0.9, γ = 1.4 is assumed

Convection from Non-insulated Wall (Q_2) (W)

$$U_2 A_{c2}(T_s - T_c) \qquad (2)$$

Convection from Insulated Bulkhead Walls (Q_3) (W)

$$U_3 A_{B1}(T_B - T_c) \qquad (3)$$

Convection from Non-Insulated Bulkhead Wall (Q_4) (W)

$$U_4 A_{B2}(T_B - T_c) \qquad (4)$$

Convection from Non-Insulated Projections (Q_5) (W)

$$U_5 A_5(T_s - T_c)\eta_f \qquad (5)$$

Convection from Floor (Q_6) (W)

$$U_6 A_6(T_f - T_c) \qquad (6)$$

Radiated Heat from Non-Insulated External Wall (Q_7) (W)

$$H_{R1} A_{c2}(T_s - T_c) \qquad (7)$$

Radiated Heat from Non-Insulated Bulkhead Wall (Q_8) (W)

$$H_{R2} A_{B2}(T_{BW} - T_c) \qquad (8)$$

Where;

$$T_{BW} = T_c + \frac{U_4}{h_i}(T_B - T_c)$$

Radiated Heat from Non-Insulated Projections (Q_9) (W)

$$H_{R3} A_5(T_{un} - T_c) \qquad (9)$$

Where;

$$T_{un} = T_c + \eta_f(T_s - T_c)$$

Solar Radiation through Passenger Compartment Windows (Q_{10}) (W)

$$0.5A_{10}\tau G \qquad (10)$$

Solar Radiation through Windscreen (Q_{11}) (W)

$$A_{11}\tau G \qquad (11)$$

Solar Radiation through Flight Deck Side Windows (Q_{12}) (W)

$$A_{12}\tau G \qquad (12)$$

Convection through Passenger Compartment Windows (Q_{13}) (W)

$$U_{13} A_{cw}(T_s - T_c) \qquad (13)$$

Convection through Windscreen (Q_{14}) (W)

$$U_{14} A_{ww}(T_s - T_c) \qquad (14)$$

Convection through Flight Deck Side Windows (Q_{15}) (W)

$$U_{15} A_{fd}(T_s - T_c) \qquad (15)$$

Occupants Metabolic Heat Release (Q_{16}) (W)

Total metabolic heat release is assumed as 116 W per person. [1]

Electrical and Avionic Heat Load (Q_{17}) (W)

500W is assumed as electrical and avionic heat release.

Total Heat Load (Q_T)

$$\sum_{i=1}^{17} Q_i \qquad (16)$$

3.2 Sample Calculation of Heat Load

Sample calculation is carried out for typical flight cases as follow as;

Case: Hot Day 25000 ft Cruise

Cabin Temperature t_c =24°C , T_c= 297.15°K (assumed)

$$t_{amb} = -9.5^{o}C,\ T_{amb} = 263.65\ K$$

$$T_s = 1 + 0.18M^2.$$

$$= 268.9\ ^{o}K$$

Mach Number (M) = 0.34

TABLE 1

THERMAL CONDUCTANCE OF EACH LAYER

LAYERS	THERMAL CONDUCTANCE (UA) (W/K)
INSULATED SKIN	27.96
UN INSULATED SKIN	68.99
INSULATED BULKHEAD	3.53
UN INSULATED BULKHEAD	0.515
FLOOR	32.52
PASSENGER CABIN WINDOWS	5.34
WINDSCREEN	9.17
FLIGHT DECK SIDE WINDOWS	9.04

TABLE 2

EQUIVALENT RADIATION COEFFICIENT FOR

NON INSULATED WALL

LAYERS	EQUIVALENT RADIATION COEFFICIENT (W/M^2K)
NON-INSULATED EXTERNAL WALL	3.58
NON-INSULATED BULKHEAD WALL	4.43
NON-INSULATED PROJECTIONS	4.09

TABLE 3

HEAT LOAD SUMMARY

HEAT LOAD	KW
Q_1	-0.78
Q_2	-1.93
Q_3	0.007
Q_4	0.001
Q_5	-0.48
Q_6	-0.455
Q_7	-0.812
Q_8	0.000532
Q_9	-0.230
Q_{10}	0.268
Q_{11}	0.595
Q_{12}	0.207
Q_{13}	-0.149
Q_{14}	-0.257
Q_{15}	-0.253
Q_{16}	1.856
Q_{17}	0.5

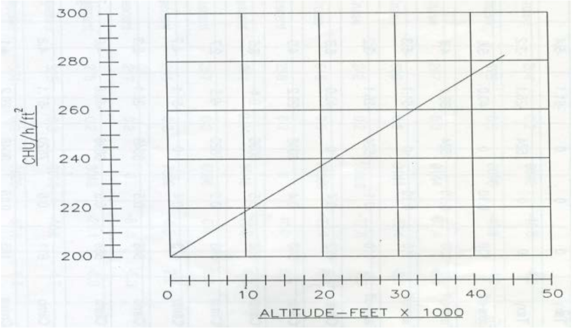

Fig 3 Solar Radiation Intensity through Altitude [3]

Total Heat Load (Q_T)

$$Q_T = \sum_{i=1}^{17} Q_i$$

$$= Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + Q_8 + Q_9 + Q_{10} + Q_{11} + Q_{12} + Q_{13} + Q_{14} + Q_{15} + Q_{16} + Q_{17}$$

$$= -0.78 - 1.93 + 0.007 + 0.001 - 0.48 - 0.455 - 0.812 + 0.000532 - 0.23 + 0.268 + 0.595 + 0.207 - 0.149 - 0.257 - 0.253 + 1.856 + 0.5$$

$$= -1.91\ KW$$

4 COOLING CAPACITY

Cooling capacity gives an idea of the ability of the pack to take out the available heat load. Cooling capacity of ECS pack can be found from the conservation of energy equation.

$$Q_c = \dot{m}_b C_p (T_{rc} - T_p) \tag{18}$$

The cooling capacity of free water is not considered

4.1 Sample Calculation

Case: Hot Day 25000 ft Cruise

$\dot{m}_b = 0.047$ Kg/s

$C_p = 1.005$ KJ/Kg °K

$T_{rc} = 296.15$°K

$T_p = 340.15$°K

$$Q_c = \dot{m}_b C_p (T_{rc} - T_p)$$

$$Q_c = 0.047 * 1.005 * (296.15 - 340.15)$$

$$= -2.07 \text{ KW}$$

The re-circulated temperature will be slightly above or below compared to the cabin temperature and is depended on the thermal load, work done by re-circulated fan, duct conductions etc, and for calculation it is assumed on the basis of available ECS test data from similar class of aircrafts.

5 RESULTS

The Table 4 below shows the heat load and cooling capacity of the pack under critical flight cases.

TABLE 4

SUMMARY OF CABIN HEAT LOAD/COOLING CAPACITY FOR CRITICAL FLIGHT CONDITIONS

SI NO	PHASE	M	ALTI-TUDE (ft)	t_{amb} (^{0}C)	Q_T (KW)	Q_c (KW)
1	CLIMB	0.44	10000	20.19	4.6	4.66
2	CLIMB	0.47	20000	0.38	0.974	1.07
3	CLIMB	0.47	25000	-9.5	-0.988	-0.992
4	CRUISE	0.3	10000	20.19	3.27	3.38
5	CRUISE	0.43	10000	20.19	4.72	4.75
6	CRUISE	0.3	20000	0.38	-0.272	-0.277
7	CRUISE	0.46	20000	0.38	0.885	1
8	CRUISE	0.34	25000	-9.5	-1.91	-2.07
9	CRUISE	0.44	25000	-9.5	-1.21	-1.23
10	DESCENT	0.2	0	40	4.48	5.089
11	DESCENT	0.24	10000	20.19	2.51	2.64
12	DESCENT	0.3	20000	0.38	-0.272	-0.422
13	DESCENT	0.33	25000	-9.5	-1.98	-1.98

6 CONCLUSION

A precise calculation of aircraft heat load would be a long process requiring detailed knowledge of the aircraft structure and of the quantities involved in the mechanism of heat pick up and interchange in the cabin. This paper has given the typical approach followed in estimating the heat loads precisely for the transport aircraft.

ACKNOWLEDGMENT

The authors wish to thank all partners and associated partners for their contribution to the program and for their permission to publish this paper

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