Environmental Control System Testing and Performance Evaluation of a Transport Aircraft

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***Abstract*—— Environmental Control System (ECS) or Air Management System is a generic term used in aircraft industry for system and equipment associated with cooling, heating, ventilation, humidity/contaminant control and pressurization within aircraft occupied compartments, cargo compartments and electronic equipment bays. It also caters to other pneumatic demands like windshield demisting, aerofoil anti-icing, door-sealing, fuel-tank pressurization and engine bay ventilation. 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.**

Ventilation to the cabin is normally through Environmental Control System (ECS), emergency back-up pressurization system and by ram air. Engines bleed air is used by the environmental control system to provide pressurization to the cabin. Refrigeration of the air is produced by a single bootstrap air cycle system (Air Conditioning Pack). The bleed air temperature control is accomplished automatically by an electronic controller in conjunction with an Electro Pneumatic Temperature Control Valve (TCV). This system is designed to maintain the cabin and crew compartment temperature in the range of 18 to 30°C up to the aircraft ceiling of altitude of 30,000 ft. This paper covers the system performance evaluation carried out for various engine power settings during ground tests on the aircraft and by empherical method. Further, instrumentation scheme adapted for measuring pressure and temperature for the above said evaluation has been discussed. Results of the tests show that the required mass flow rate and condition of the air entering in to the cabin is met, thus ECS performance is satisfactory.

Keywords: ECS, Engine bleed, TCV, Air cycle

I. INTRODUCTION

A. Description of the System

1) General: The 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 Figure 1. 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. The conveyance of air is through pipe routings. This system is designed to maintain cabin and crew compartment temperature in the range of 18 to 30°C up to the aircraft ceiling of altitude of 30,000 ft.

This paper covers the system performance evaluation carried out for a typical engine power setting at flight idle condition and the system tests were carried out on aircraft during engine ground runs and by empherical method. Further, instrumentation scheme adapted for measuring pressure and temperature for the above said evaluation has been discussed. Results of the tests show that the required mass flow rate and condition of the air entering in to the cabin is met and ECS performance is satisfactory.

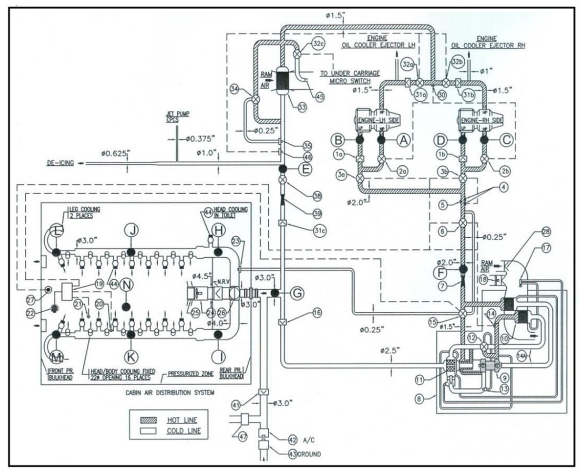

Fig.1 ECS Schematic

2) System Operation: With reference to Fig.1 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 till completion of takeoff ground run 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 recirculated 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 recirculated 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.

II. Performance Evaluation

B. Test Case and Assumptions

ECS on ground is designed with the following engine operating condition and with certain assumptions.

Engine operating condition:

Flight idle: Bleed air limit : 12 Lb/min per engine
Bleed air pressure : 41 psia (minimum)
Bleed air temperature : 491 °K
Cabin Temperature : 18 -30°C (with Cabin interiors)

Assumptions:

The bleed air required for ejector is 5lb/min/engine and therefore the bleed available for Environmental Control System (ECS) is limited to 7lb/min per engine.

Ambient condition:

Altitude: 2885ft
OAT = ISA+20°C.

C. Test setup and results

The test setup refer Fig 1 consists of pressure and temperature measurements staring from location A of LH engine HP line to N of Cabin. It can be seen from the test results Table.1, for the flight idle, which is the typical ground operating condition; ECS performance is meeting the design requirements.

TABLE I
RESULTS

S.No	**ECS Parameter**	**OEM Typical values**	**EGR Test Data** (without cabin interiors)
1	ECS Pack inlet bleed air pressure	Below 30 ± 3 psig	24 psig
2	ECS Pack inlet bleed air Temperature	Below 265 ± 5 °C	180ºC
3	Fresh air Temperature (Inlet to mixing chamber)	Auto mode	• Cold ï Temperature reduced to 3 ºC from 36 ºC in 5 min • Normal - Temperature increased to 9 ºC from 8 ºC in 5 min • Hot ï Temperature increased to 9.2 ºC in 5 min
		Manual mode	• Cold ï Temperature reduced to 9 ºC from 21 ºC in 5 min • Normal - Temperature increased to 12 ºC from 9 ºC in 5 min • Hot ï Temperature increased to 72 ºC from 12 ºC in 5 min
4	Cabin Air Temperature	18 ï 30 ºC (Auto mode) (with Cabin interiors)	Cold ï Temperature reduced to 31 ºC from 36 ºC in 5 min Normal - Temperature increased to 29.5 ºC from 31 ºC in 5 min Hot ï Temperature increased to 29.5 ºC in 5 min
		1 ï 62.5 ºC (Manual mode) (with Cabin interiors)	Cold ï Temperature reduced to 29 ºC from 30.5 ºC in 5 min Normal ï Temperature increased to 29.5 ºC in 5 min Hot ï Temperature increased to 38 ºC in 5 min
5	Cabin duct air Temperature	1ºC < T < 80ºC	72ºC (Item No 23 limits to below 80 ± 5 ºC
6	1.5ò PRSOV Upstream Temperature	35 ± 5ºC < T < 105 ± 5ºC	33ºC
7	Fresh air mass flow to cabin	Min 8.8 lb/min	17.4 lb/min

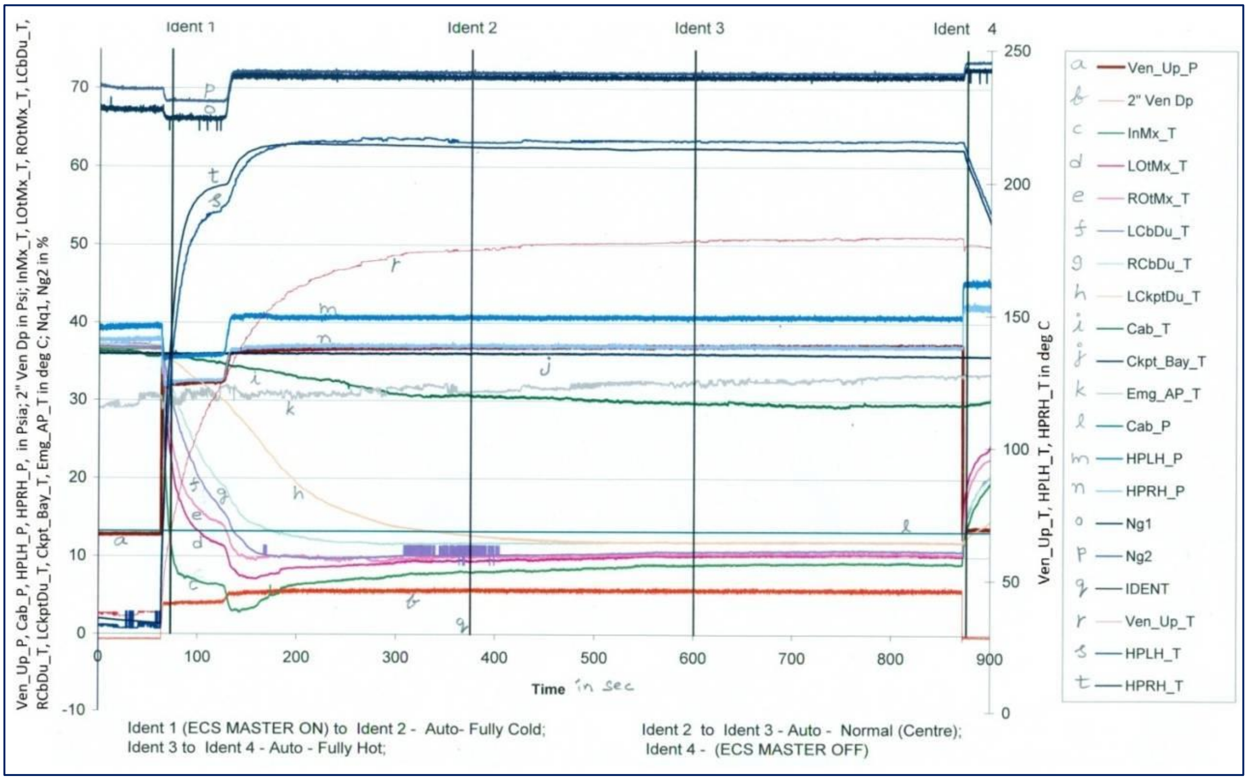

Fig.2 ECS Normal ï Auto mode

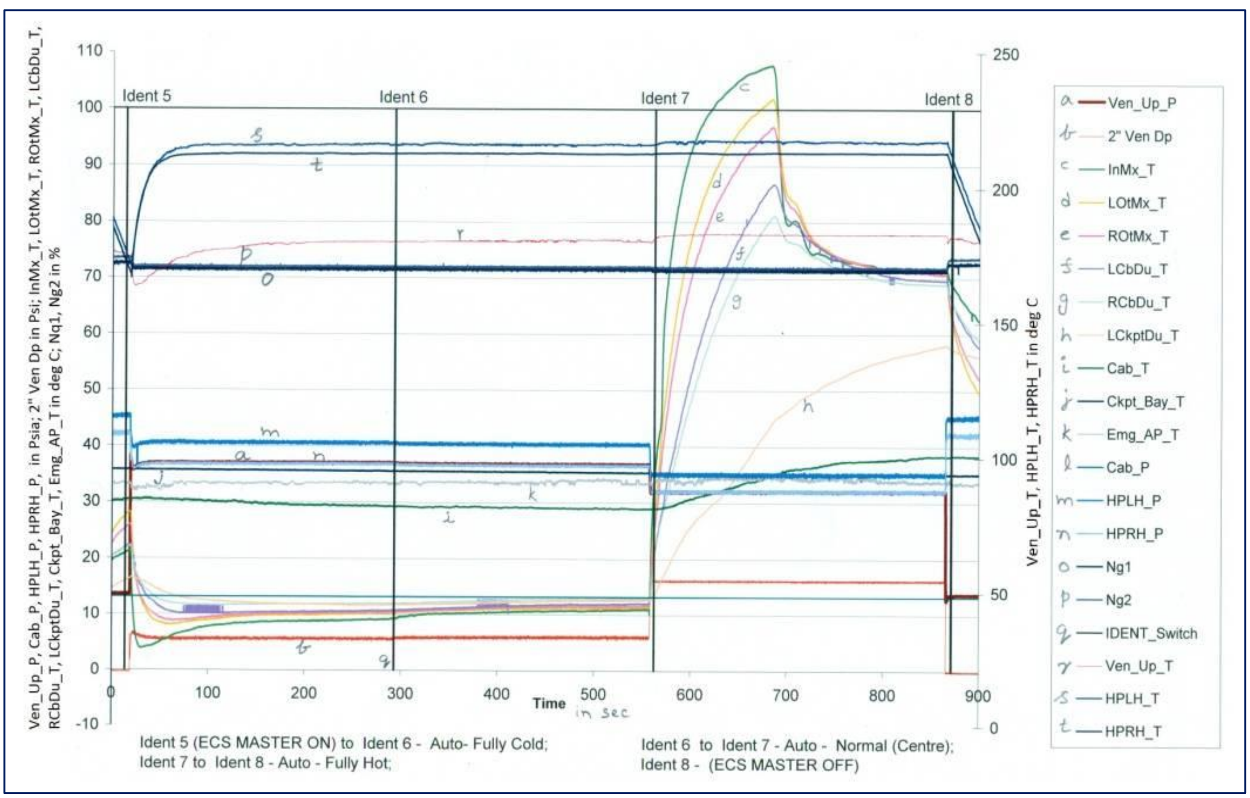

Fig.3 ECS Normal ï Manual mode

It is observed that the important system performance indicators such as fresh air temperature and mass flow rate values are 0.5ºC and 15.6 lb/min respectively and it is in good agreement with the expected values which meets the base line requirement.

Referring to Figure 2, when ECS switched ON, TEMP SEL knob in fully cold condition (Maintain the condition to allow Cabin temperature to stabilize),it is observed that at Ident 1, parameter ‘a’ increases (from 13 psia to 37 psia) with engines bleed air flow. This confirms LRU Item No’s (2, 3, and 6 electrically open) and LRU item No’s 1, 7, 8, 15, 16, 17, and 28 are functional and ECS Normal operation confirmed satisfactory. It is also observed from Fig 3 between Ident 1and Ident 2, the parameters (c, d, e, f, g, and h) reduced (from 36°C to between 8°C and 12°C). This confirms that LRU Item No’s 19, 20, 21, and 22 are functional. At the end of 5 min the Cabin temperature reduced to 31°C from 36°C.

Referring to Figure 3, when ECS switched ON, TEMP SEL knob in fully cold condition (Maintain the condition to allow Cabin temperature to stabilize), it is observed that at Ident 5, parameter ‘a’ increases (from 13 psia to 37 psia) with engines bleed air flow confirming LRU Item No’s (2, 3, 6 electrically open) and LRU item No’s 1, 7, 8, 15, 16, 17, and 28 are functional and ECS Normal operation confirmed satisfactory. It is observed from Fig 4 between Ident 5 and Ident 6, the parameters (c, d, e, f, g, and h) reduced (from between 20 °C and 24°C to between 9°C and 12°C). This confirms that LRU Item No’s 19, 20, 21, and 22 are functional. At the end of 5 min the Cabin temperature reduced to 29.5°C from 31°C.

Referring to Figure 3, when knob TEMP SEL rotated to fully right condition (Maintain the condition to allow Cabin temperature to stabilize), it can be seen that between Ident 7 and Ident 8, the parameters (c, d, e, f, g, and h) increased (from between 10.5 °C and 12.5°C to maximum temperatures between 81°C and 107°C and stabilized to between 68°C and 72°C). This behavior confirms that LRU Item No 23 functional, limiting the Cabin duct temperature to below 80±5 °C and LRU Item No’s 19, 20, 21, and 22 are also functional. At the end of 5 min the Cabin temperature is observed to be 38°C.

D. Calculation of mass flow (Flow Measurement – B.S. 1042:1943, British Standards Institution & Methods for the Measurement of Fluid Flow in Pipes- B.S. 1042: Part 1: 1964”, British Standards Institution.)

$$Q = 7859 \text{ x } C.Z.d^2.E \text{ x } \sqrt{h} \text{ x} \sqrt{\frac{P_1}{T\check{u}}} \text{ x } N..........(1)$$

No Q = Rate of flow in Standard cubic feet per hour;

C = Coefficient of discharge of the Venturi tube; the ratio of the actual discharge to the theoretical discharge calculated from the elementary energy equation (Bernoulli’s theorem)

Z = Product of three separately specified multipliers for viscosity Rd, Pipe size D and expansion Ů

d = Diameter (Throat) in inches of Venturi at the working temperature.

Velocity of approach factor

$$E = \frac{1}{\sqrt{1-m^2}}.....................................(2)$$

m = Area ratio $\frac{d^2}{D^2}$

h = Differential pressure, inches of water at 60ºF (under air)

P1 = Absolute pressure of air. Lb/in2; measured at the position of the high pressure tapping.

T = Absolute temperature of air °F. + 460 measured at the position of the high pressure tapping.

ǔ = Specific gravity of dry gas, relative to dry air at the same pressure and temperature (For air ǔ = 1)

N = Correction of water vapour in gas or air: (For air N=1)

D = Diameter of main pipe in inches

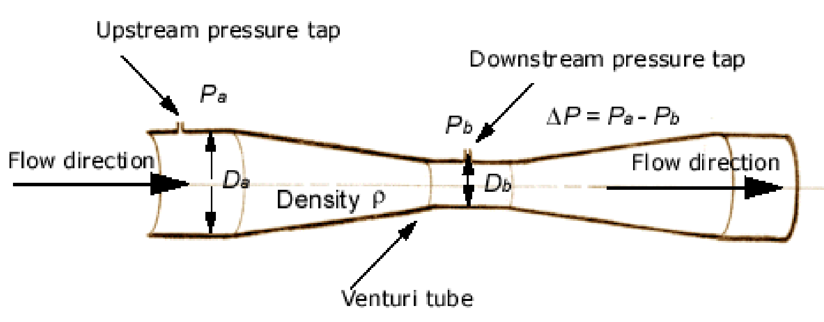

Fig.4 Schematic of Venturi

ȷ = Density, $\frac{14.7 \times 144}{96 \times (273+15)}$ = 0.0765 Lbs/ft3

D = 49.4 mm = 1.94 in

d = 21 mm = 0.83 in

$$m = \frac{d^2}{D^2} = \frac{0.83^2}{1.94^2} = 0.183 \text{..............................(2)}$$

$$E = \frac{1}{\sqrt{1-m^2}} = \frac{1}{\sqrt{1-0.183^2}} = 1.017 \text{.........................(3)}$$

C = 0.99 (assumed)
N = 1; Z = 1
From ground run h = Δp = 6.1 psi
h = 6.1 psi = 6.1 x 27.68 = 168.85 in of WG
P1 (Bangalore atmosphere) = 36.8psia
ECS Pack inlet Temp. = 180 ºC = 356 ºF
T = 356 ºF + 460 = 816

$$Q = 7859 \text{ x } C.Z.d^2.E \text{ x } \sqrt{h} \text{ x} \sqrt{\frac{P_1}{T\delta}} \text{ x } N \text{....................(4)}$$

$= 7859 \text{ x } 0.9^* \text{ x}1\text{x } 0.83^2 \text{x}1.017 \text{ x } \sqrt{168.85} \text{ x } \sqrt{\frac{36.8}{816 \text{x } 1}} \text{ x } 1$

= 7859 x 0.9* x 1 x 0.6889 x 1.017 x 11.88 x 0.208 x 1

Q = 13646.83 stdcu.ft/hr

Q= (13646.83 x 0.0765) / 60

Q = 17.4 lbs/min

*Co-efficient of discharge Cd of 0.9 is assumed for the flow through Venturi

III. Conclusion

It can be seen from the test results for the flight idle, which is the typical ground operating condition; ECS performance is meeting the design requirements. It is observed that the important system performance indicators such as fresh air temperature and mass flow rate values are 3°C and 17.4 lb/min respectively and it is in good agreement with the expected values which meets the base line requirement.

Acknowledgement

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[1] British Standards Institution, *Flow Measurement – B.S. 1042,* 1943.
[2] British Standards Institution, *Methods for the Measurement of Fluid Flow in Pipes- B.S. 1042, Part 1,* 1964.