International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

Qualification of an aircraft compact heat exchanger

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Abstract

Compact heat exchangers play a vital role in various process industries, nuclear power plants, aerospace applications, etc. Newly designed compact heat exchangers would be subjected to various milestone tests starting from the design stage till it reaches the final operational maturity level. In particular, the qualification of compact heat exchangers used for aerospace applications are more stringent as they work in arduous operating conditions. This paper elucidates the various tests that an aircraft compact heat exchanger undergoes and provides details of the state-of-the-art qualification test facility required for testing the mechanical integrity of compact heat exchanger, testing process and test results.

Nomenclature

GTRE - Gas Turbine Research Establishment
ADA - Aeronautical Development Agency
CHE - Compact Heat Exchanger
PSV - Pneumatic Shut-off Valve
FCV - Flow Control Valve
PCV - Pressure Control Valve
TCV - Temperature Control Valve
QAV - Quick Actuating Valve

σ - Allowable stress
EH - Electric Heater
CH - Chilling Plant
C - Cooler
JC - Jacket Cooler
FT - Flow Transmitter
S - Silencer
MS - Moisture Separator

Subscripts

HE - Heat Exchanger line
BP - Bypass line
L - Minimum (Low) Condition stream
H - Maximum (High) Condition Stream
RT - Room temperature
WT - Working temperature

1. Introduction

Aircraft consists of numerous systems and equipment. Heat exchangers are one of the equipment used extensively in the aircraft for carrying out various types of processing such as heating, cooling, etc. using various media. Compact heat exchanger is one of the most efficient equipment to transfer heat from one medium to another. A compact heat exchanger is a type of heat exchanger which uses metal plates to transfer heat between two streams of fluid. Compact heat exchangers are generally defined as one having a heat transfer area per unit volume greater than 700 m^2 / m^3 [1].

The compact heat exchangers are being used in a large number of industries. The application determines the material of construction, fabrication & development of the compact heat exchangers. In compact heat exchangers the fluids are exposed to a much larger surface area which facilitates high heat transfer rate and give high effectiveness. These heat exchangers are widely used in aerospace applications due to their less weight, greater compactness and higher performances which are essentially due to the improved heat transfer surfaces. In aerospace industries where premium is placed on size and weight without compromising on performance aspects, these compact heat exchangers are principally utilized. Compact heat exchanger generally consists of thin plates & fins which are stacked together and are normally brazed or welded.

The aircraft heat exchangers during their operation are subjected to arduous conditions [2]. Hence the developmental compact heat exchangers for aircraft have to be extensively tested for their endurance life so as to qualify for their airworthiness. In this paper the qualification of a typical compact heat exchanger used in a combat aircraft is illustrated and its test results are discussed. The details, design data with respect to heat exchanger could not be provided due to confidentiality.

2. Developmental Tests for Aircraft Heat Exchangers

Abinitio designed compact heat exchangers for aerospace application is required to be evaluated in two phases namely
(i) Performance evaluation and
(ii) Qualification for airworthiness.

2.1. Performance Evaluation Tests

These tests are conducted to obtain complete performance applicable to full range of aircraft operating conditions for various flow rates, pressures and temperatures. Steady state conditions of hot air side and coolant air side are provided at inlet of the heat exchanger corresponding to various altitudes and Mach numbers experienced during flight. Extensive instrumentation is carried out on heat exchanger, inlet and outlet streams and the acquired data is analysed for performance evaluation.

2.2. Qualification Tests

The aircraft heat exchangers experience arduous and extreme working conditions during their operation. Hence the mechanical integrity and endurance life of heat exchanger needs to be estimated before leading to flight clearance.

3. Qualification tests for aircraft heat exchangers

Military aircrafts and its various systems operate under arduous conditions within their flight envelope. In a typical one hour sortie consisting of take-off, combat mission and landing, the aircraft and its sub-systems undergoes 3 to 5 cycles of operating conditions varying from maximum to minimum. Hence during its service life, the aircraft as well as its various sub-systems such as compact heat exchangers undergoes many maximum - minimum operating conditions (cycles). The aircraft compact heat exchanger which is the test article considered, is subjected to such rigorous and varying dynamic conditions and is required to be tested to similar loading so as evaluate its design intent.
The various qualification tests which are required to be carried out on the compact heat exchanger based on MIL standard [3] are

3.1. Proof Pressure Test

Proof pressure test on heat exchanger will be carried out using water with 1.5 times the operating pressure.

3.2. Pressure Cycling Test

Hydraulic oil at room temperature is used as medium for carrying out pressure cycling. Test Pressure for Pressure cycling = 1.5 * Design Pressure * σ_{RT} / $\sigma_{WT.}$ The pressure is cycled from normal ambient pressure to test pressure in 2 sec. The heat exchanger is subjected to 50,000 cycles.

3.3. Thermal Shock

Heat exchanger is subjected to thermal shock by keeping in hot & cold chambers for 3 cycles. The hot and cold chamber temperature will be the maximum and minimum temperature to which heat exchanger is subjected in its operating envelope.

3.4. Burst Pressure Test

Burst pressure test is carried out on the heat exchanger using hydraulic oil for a test pressure with suitable compression pumps.
Burst pressure = 2.5 * max. operating pressure * σ_{RT} / σ_{WT}.

3.5. Vibration Test

Heat Exchanger is filled with hydraulic oil, pressurized for max operating pressure and vibrated for one hour in each direction.

3.6. Acceleration Test

Heat exchanger is simulated for maximum to minimum acceleration (‘g’ loads) using a centrifuge with one min. duration in each axis.

3.7. Mechanical Shock Test

This is done to check the mechanical strength of mounting brackets. This test is done for +15 G. Heat exchanger is mounted on a table and pushed from a height of 500 mm in 11 millisec duration for all axis.

3.8. Humidity Test

The heat exchanger is kept in humid chambers of 90 % RH for 28 days. Physical & chemical deterioration of material of heat exchanger is evaluated.

3.9. Salt Fog Test

Heat exchanger is kept in high salt fog simulated chamber for 28 days and is evaluated for corrosion.

3.10. Fungus Test

This test is carried out by growing fungus and it is evaluated for fouling factor.

3.11. Combined Pressure, Temperature & Flow (CPTF) Cycling Test

The most stringent qualification test on the compact heat exchanger is the combined pressure, temperature and flow [CPTF] cycling on heat exchanger. This test is carried out by cycling all inlet streams simultaneously from minimum to maximum conditions {i.e. Pressure, Temperature & Flow}. This cycling would simulate the actual aircraft operating conditions to a maximum extent. The maximum and minimum conditions, time for cycling, etc. in turn are derived from aircraft flight envelope.

4. Experimental evaluation of endurance life

Literature pertaining to direct prediction of endurance life of compact heat exchangers theoretically is not available in open literature and is difficult to carry out due to complexities involved in the computation. Hence endurance life of aircraft heat exchangers has been experimentally evaluated by subjecting them to

ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

CPTF cyclic test. To carry out combined pressure, temperature & flow cycling tests on heat exchangers, the pressure, temperature & flow conditions of all inlet streams i.e. hot stream and coolant stream, are varied from minimum to maximum condition as per the diagram shown in **Fig. 1** as per MIL standard [3].

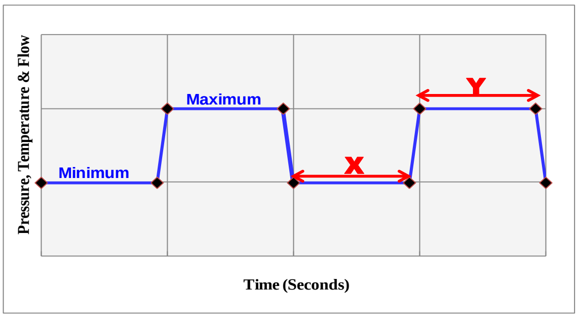

Fig. 1 Cycle Diagram

The inlet streams are required to be kept in minimum condition for a given time (say ‘X’ sec), raised from minimum to maximum condition quickly (2-3 sec), kept in maximum condition for a given time (say ‘Y’ sec) and brought back to minimum condition quickly in 2-3 seconds. This constitutes one full cycle. The heat exchanger was subjected to hundreds of cycles to evaluate its life. The time interval of ‘X’ and ‘Y’ are decided based on duty cycle / combat envelope.

5. Conceptualisation of Qualification Test Facility

An exclusive test facility was designed and established to carry out CPTF cyclic tests on aircraft compact heat exchangers so as to evaluate the endurance life and qualify them. The existing air supply facility was utilized for this purpose. This facility supplies two streams of air simultaneously, the design conditions of which are given below :

Stream-1 : 550 kPa, 180 °C & 22 kg/s.
Stream-2 : 3000 kPa, 160 °C & 6 kg/s.

Stream-1 was utilized for simulating the coolant air and stream-2 for simulating the hot air. **Table-1** shows the minimum & maximum conditions of pressure, temperature and massflow of coolant air and hot air required to be simulated and cycled at inlet of the compact heat exchanger.

Table -1 Conditions for cycling

Process conditions	Hot Air		Coolant Air	
	Min	Max	Min	Max
Pressure [kPa]	400	650	10	80
Temperature (°C)	350	600	40	121

As the conditions required at the inlet of the heat exchangers (Table-1) are different from the conditions of the air available from the air supply station, the supplied air needs to be processed using various equipment to achieve the required conditions given at Table-1. The processed inlet streams are cycled as per the cycle diagram shown in **Fig. 1**. For this cyclic test, hot air stream minimum condition of 400 kPa, 350 °C and 28 kg/min and maximum condition of 650 kPa, 600 °C and 35 kg/min has to be simulated at inlet of CHE. Though it is possible to raise the pressure from 400 kPa to 650 kPa in 2-3 seconds, it is not possible to raise the temperature from 350 °C to 600 °C in this duration. Hence using a single stream of air for carrying out the cycling for the given conditions is not possible. Hence a unique technique using Quick Actuating Valves (QAV) was incorporated to meet this cycling requirement.

The two streams of air tapped from supply station are processed through various equipment to obtain the conditions of four streams of air required at the inlet to the heat exchanger given at Table 1. In all the four streams, these conditions are achieved and stabilized in the bypass mode, before the cycling is started. In this facility, four independent streams of air corresponding to the max. and min condition of hot and coolant air (Table-1) are processed before hand and kept ready and stabilized in bypass mode. Once the conditions are achieved in the bypass mode, then the cycling is carried out using the quick actuating valves.

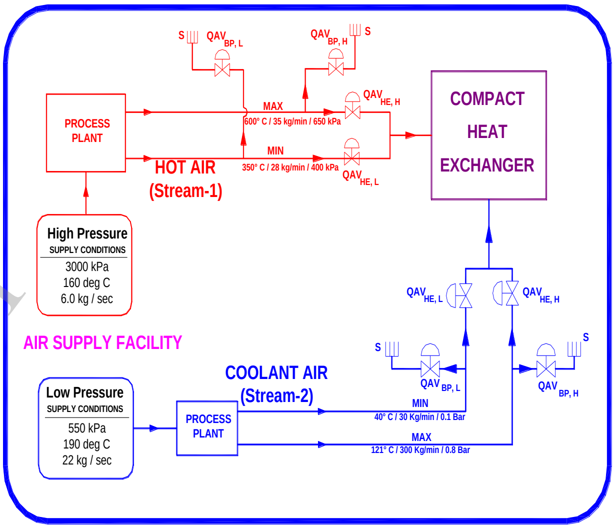

Fig. 2 Quick Actuating Valve Mechanism

As shown in **Fig. 2**, Four number of Quick Actuating valves (QAV_{BP-L}, QAV_{HE-L}, QAV_{BP-H} & QAV_{HE-H}) are used to cycle the hot air stream from minimum to maximum condition. When the **minimum** condition of the hot air **enters** the Heat exchanger, the **maximum** condition stream of hot air is **bypassed** to the ambient through the appropriate QAV. After ‘X’ seconds, the QAV in the minimum stream towards the heat exchanger closes and that in the bypass line opens and vents it out to the ambient. At the same time, the QAV in the hot air maximum stream towards the heat exchanger opens and allows the flow to the heat exchanger. Similarly in the coolant stream, four numbers of QAVs are used to cycle it from min. to max. condition and vice versa. The operation of all QAVs are synchronized using the dedicated control system.

6. Major equipment in the facility

Based on the above QAV mechanism, the engineering layout of the entire facility was finalized as shown in **Fig. 3**.

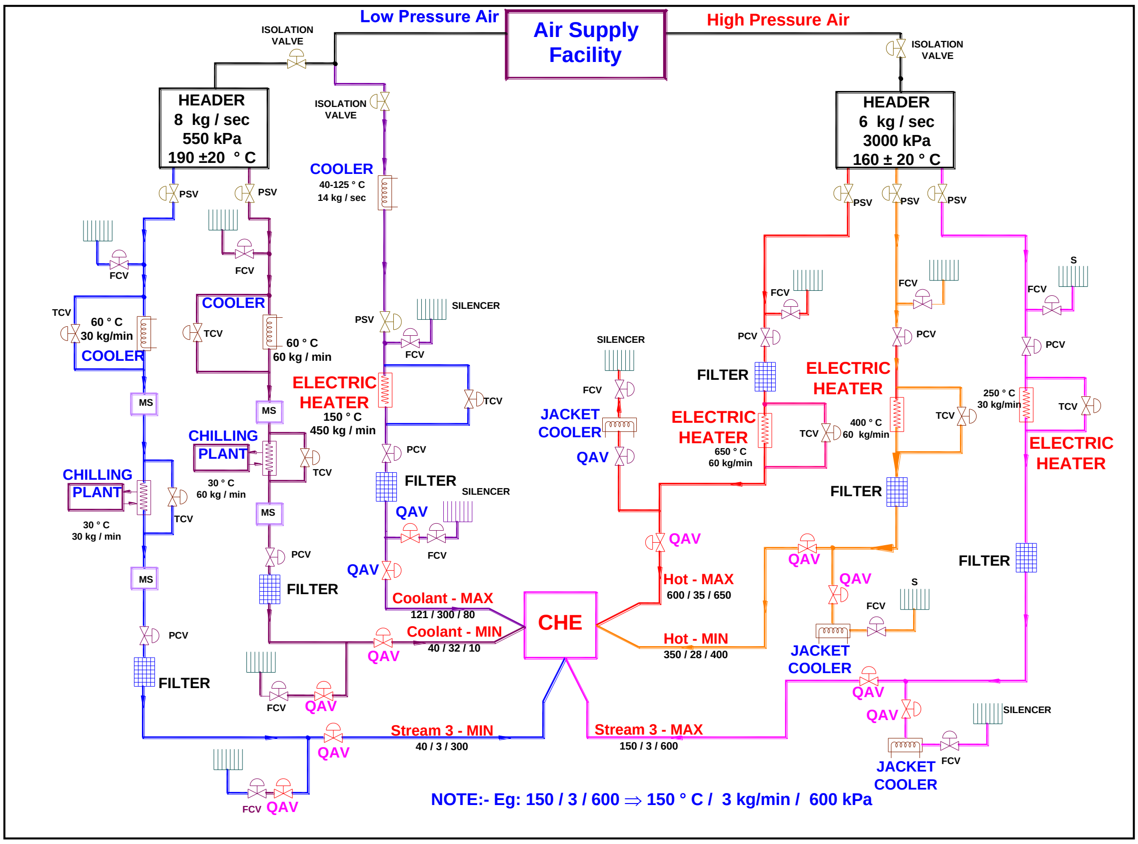

Fig. 3 Layout of CHE Cyclic Test Facility

The facility was designed for carrying out qualification testing on aircraft heat exchangers having three inlet streams.

The two streams of air from the air supply facility is in turn divided into six streams and processed separately to cater for each of the conditions. The six different streams are designated as C_A, C_B, C_C, H_A, H_B & H_C. These streams are processed using various equipment such as the electric heaters, coolers, chilling plants, filters, control valves to control pressure, temperature & flow. To simulate the minimum and maximum flow conditions of test heat exchanger given in **Table-1, four** streams, viz., $\mathbf{C_A}$, $\mathbf{C_B}$, $\mathbf{H_A}$ and $\mathbf{H_B}$ are utilized.

Line C_A provides the maximum condition of the coolant air.

Line C_B provides the minimum condition of the coolant air.

Line H_A provides the maximum condition of hot air.

Line H_B provides the minimum condition of the hot air.

Line C_C and **Line H_C** are provided to cater for future CHE having three streams and would provide the minimum and maximum conditions respectively.

The entire plant & piping were designed as per ASME pressure vessel code [4] and Power Piping code [5]. The complete facility with its piping network was subjected to flexibility analysis for finalising the support structure and for accommodating the thermal expansion of the piping structure. Using the flexibility analysis, proper supporting structures and the expansion loops were provided to avoid failures. The equipment and the piping in C_A, C_B & C_C streams are designed to withstand 6 bar pressure and those in H_A, H_B & H_C streams have been designed to withstand pressure of 30 bar. The facility has a data acquisition and feedback control system which controls and health monitors the entire plant. The control system also synchronises the operation of QAVs during cycling. The data acquisition system acquires pressure, temperature and massflow measurement at various locations in the facility. The entire test facility has been extensively instrumented to control and monitor various equipment in the facility. The inlet and outlet conditions of the hot and coolant air streams were instrumented to measure the pressure, temperature and the massflow.

Pneumatic Shut-off Valves (PSV) are located at the inlet in each stream of the facility and isolates the facility from air supply facility.

To achieve the required pressure, temperature and massflow in each stream, the following methodology was applied. Initially, the massflow in each stream was corrected by having a flow control valve (FCV) in the first bypass. By controlling this valve, required massflow of air was provided to the heat exchanger under test. A pressure control valve (PCV) in-line with the test heat exchanger controls the pressure as per the requirement. This air passes through a 25 micron filter to supply clean air. Finally the temperature was achieved by passing through an electric heater or cooler and / or chilling plant as per the requirements. A temperature control valve (TCV) is also provided for accurate control of temperature. Electric heater (EH) - five numbers, cooler (three numbers) and chilling plants (two) have been provided in the respective streams to achieve the necessary temperature. The facility has the following five electric heaters viz., EH1A & EH1B in H_A line, EH2 in H_B line, EH3 in H_C line and EH4 in C_A line. Each electric heater uses three types of heating viz., fixed bank, control bank and thyristor bank. These banks are switched on and controlled by the Plant Control System for accurate control of the temperature within the tolerance limits of ± 2 °C. Three coolers are provided in the facility one each in $\mathbf{C_A}$, $\mathbf{C_B}$ & $\mathbf{C_c}$ lines. Two Chilling plants are provided one each in $\mathbf{C_B}$ & $\mathbf{C_c}$ lines.

The processed clean air with the pressure, temperature and massflow as per the requirements of the test heat exchanger, either passes through to the test heat exchanger through QAV_{HE} or bypassed to the ambient through QAV_{BP} in the final bypass line. A flow control valve (FCV) located in this second bypass line simulates the heat exchanger and provides the necessary load during the bypass mode.

7. Test Results & Discussions

The cyclic test facility has been extensively used for endurance testing of CHE. The results of the cyclic test have been analysed and resulted in valuable data to designer and confidence to the customer.

Fig. 4 & 5 shows typical pressure and temperature cycles carried out on CHE. The variation of inlet, outlet pressures and temperatures are plotted for both hot and coolant streams.

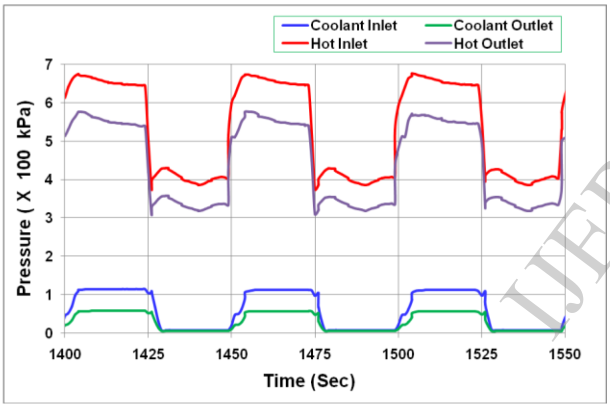

Fig. 4 Pressure Cycles

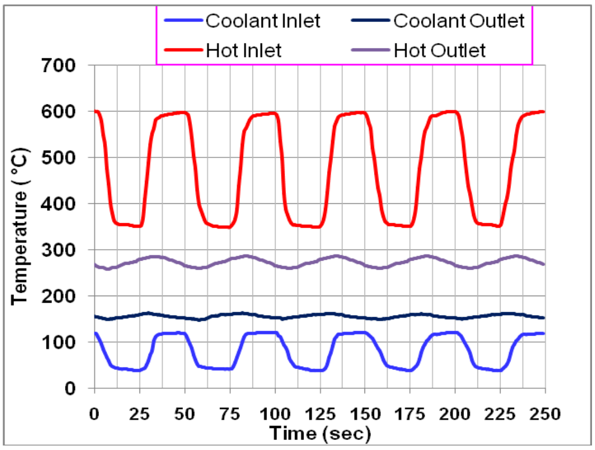

Fig. 5 Temperature Cycles

The pressure, temperature & massflow are kept at minimum condition for 23 seconds and raised from minimum to maximum condition in 2 seconds, kept in maximum condition for 23 seconds, brought back to minimum condition in 2 seconds. The above mentioned variation constitute one cycle for a specific CHE.

It can be seen from the above graphs that for both hot and coolant air, outlet pressure variation follows the inlet pressure variation. Both streams outlet temperature are not following the same pattern as that of inlet temperature variation, i.e. when the hot stream inlet temperature is at max condition (600 °C) of the cycle, hot stream outlet temperature is tending towards the minimum and vice-versa. On further analysis, it is found that during the max. condition, higher coolant massflow (300 kg/min) passes through heat exchanger leading to lower outlet temperatures of hot air and lower temperature pick-up of coolant air.

Leakage test was conducted at the end of every 100 cycles of CPTF cyclic tests for ascertaining the structural integrity of the heat exchanger. CHE has withstood 1100 cycles. Based on the test results, the compact heat exchanger is cleared for limited flying hours.

8. Conclusion

The facility was extremely useful in carrying out the combined pressure, temperature & flow cycling on compact heat exchanger resulting in qualifying the newly developed heat exchanger for limited flight trials. However the setting up of a facility and the cost of testing are comparatively high and requires long lead time. Alternatively, to evaluate the reliability and safety of the heat exchanger, accurate thermo-mechanical analysis of CHE is needed [6]. The thermal hydraulics phenomena in CHE's complex geometry must be analysed at the component scale during the steady-state operation as well as during flow transients.

Due to complex geometry of heat exchanger, the analysis is tedious, time consuming, iterative and required to be carried out using computational methods. CFD is required to arrive at the fluid temperature distributions of the compact heat exchanger. Applying the resulting temperature and flow distributions from CFD which includes the complicating effects of temperature dependent thermo-physical properties, we obtain the material temperature distribution. Furthermore the temperature distribution of CHE will serve as a starting point for the finite element analysis on the CHE which results in Von Mises stress distribution. This stress state is imposed on unit cells to arrive at the peak stresses. This can then be utilized for arriving at the failure criteria [7]. The stress levels needs to be computed for the maximum as well as the minimum condition for evaluating the fatigue and creep life.

Acknowledgements

Authors acknowledge Dr. C.P. Rama Narayanan, Director, GTRE and Dr. C. Ranganayakulu, Sc. 'G', ADA for supporting in publishing of this paper. Authors also express their thanks to Mr. M. Palanikumar, GTRE for assistance rendered during the experimental work and in preparation of the manuscript.

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