

WINDMILL POWERED COOLING FOR AVIONICS

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ABSTRACT

As part of an international project, in the early '90s the FIMAC Company developed a ram air powered cooling system (Cooler) able to keep below 70 °C the cold walls of avionic equipment on board of a fighter plane Pod, without external power input and providing refrigerating power up to 1500 W.

The Cooler obtains energy from the airflow gathered at the Pod ram intake that crosses the air path of the Cooler. In its path, the air drives a Ram Air Turbine (RAT) that is the windmill prime mover for the refrigerant circuit, where the hybrid cooling capabilities of expanding air and a reverse Rankine cycle, based on organic fluid refrigerant, are exploited to a maximum.

A Multivortex[®] Compressor driven by the RAT provides the gas compression phase of the refrigerant cycle .

A compact heat exchanger Condenser rejects into the RAT exhaust air the heat from the refrigerant gas condensation phase.

Useful heat subtraction (liquid refrigerant expansion and evaporation phases) takes place in a set of Cold Walls located in the frame of the payload avionic boxes.

Peculiar features of the Cooler, beyond conventional refrigerators, are:

- Lower condensation temperature in the correspondent speed condition. Because of the mechanical power supplied to the RAT, the incoming air cools itself and performs a thermal exchange at a temperature lower than the stagnation temperature TRAM (this is the so-called "hybrid" cycle effect).
- Liquid Booster Pump (on the same shaft of the Compressor) delivering sub-cooled liquid flow to the Cold Walls.
- Trimming circuit of the refrigerant circulating volume (circuit charge) composed by a Tank with an electrically powered Pump and solenoid valve. Flooding or draining the Condenser, transferring fluid to and from the tank, determines the charge control.
- Air outlet nozzle control device, composed by a louver valve and hydro-mechanical Actuator, operated by the same refrigerant. This device modulates the air outlet area to keep the airflow and the RAT speed controlled and adequate to the operating conditions.

The operation of the Cooler involves the combination of three functionally interacting loops:

- Air circuit for power extraction and heat rejection.
- Vapor cycle based on organic refrigerant for two-phase cooling of the Cold Walls.
- Control circuit for the determination of the active charge of the refrigerant.

The above operating loops, that enable the Cooler to operate over the aircraft flight envelope, are intrinsically stable and widely self-adjusting, while interaction effects are minimized to avoid hunting.

The main control effect, the actuation of the air circuit control louver valve, is self-regulating by action of a refrigerant fluid operated, pressure-controlled actuator.

An integrated Electronic Control Unit receives pressure signals from the refrigerant cycle and operates the refrigerant charge control to optimize the working condition, delivering in the same time status information to the aircraft.

1. INTRODUCTION

On a modern fighter aircraft, the installed electronic equipment, used both as navigation aid and for tactical use, needs to be cooled to remove internal dissipated heat and to grant the full performance over the demanding environment (particularly at high speeds).

On the other side, the energy amount to drive any cooling equipment is perceived as a “parasite” use, because of the necessity to fully exploit the on-board generated electrical power for active duties on the aircraft.

In this perspective, the benefits of a self powered cooling apparatus have led the Engineering department of FIMAC Company to design and develop a line of ram air powered, windmill driven cooling/refrigerating machines that proved to be an effective answer to the problem.

2. THE COOLER

The windmill driven cooling system, hereinafter “Cooler”, is made of different components, each covering an important role in the performance of the whole machine. Figure 1 presents the hydraulic circuitry of the Cooler, highlighting the major segment listed in the following:

- Air Circuit
- Ram Air Turbine
- Refrigerant Condenser Heat Exchanger
- Airflow control Louvers
- Louvers Hydraulic Actuator
- Air Nozzle Control Spring
- MVX Compressor
- Liquid Booster Pump
- Cold Walls refrigerant Metering Nozzles

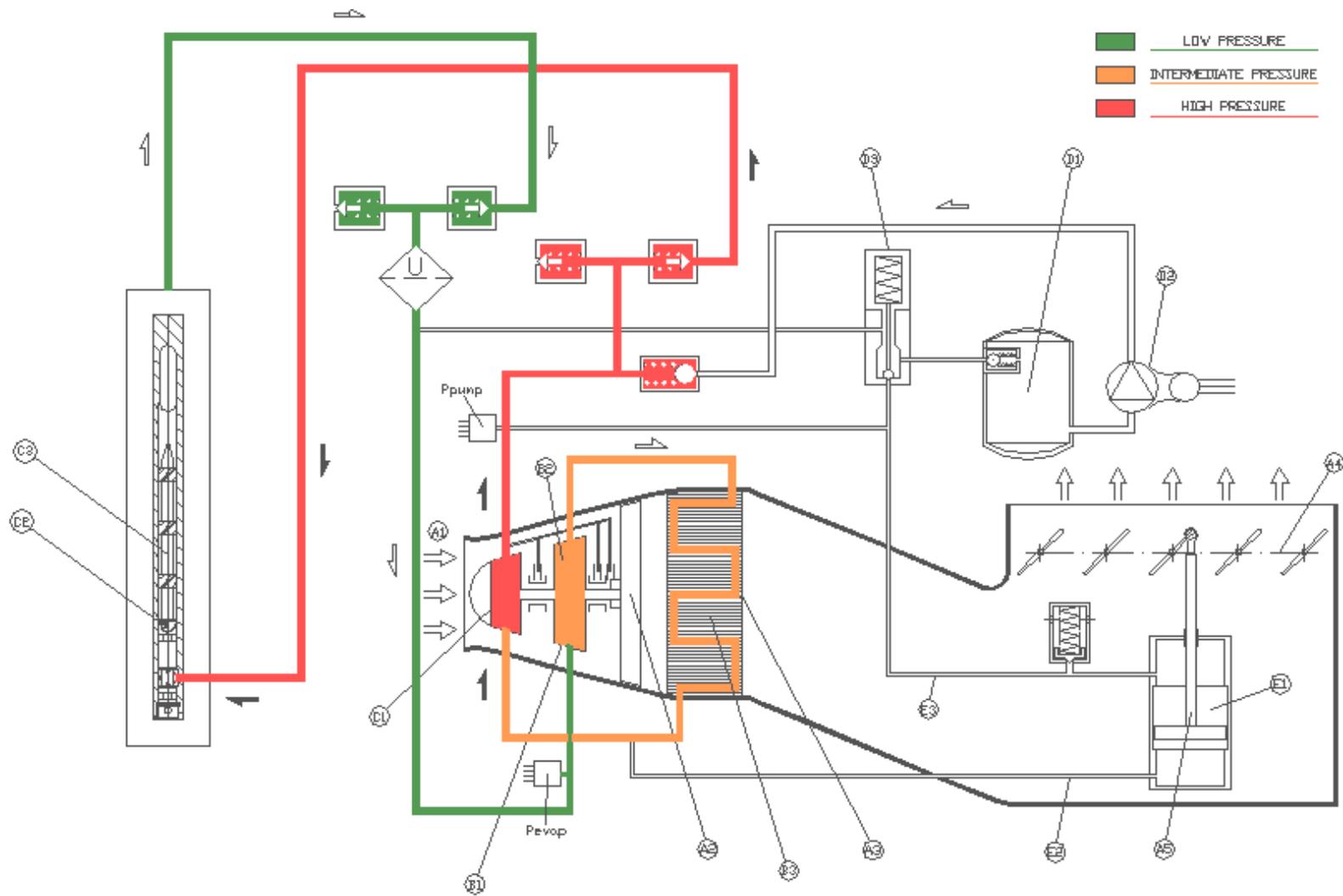


Figure 1: Schematic of the Cooler

2.1 AIR CIRCUIT

The Air circuit represents the “engine” of the Cooler. The air, drawn at the external dynamic intake, crosses the Ram Air Turbine (RAT) transferring power to and from the Cooler. With reference to the Figure 1, the following significant components are highlighted:

- A1: Air Inlet Duct.
- A2: Ram Air Turbine.
- A3: Refrigerant Condenser Heat Exchanger.
- A4: Airflow Control Louvers.
- A5: Louvers Hydraulic Actuator.
- E1: Air Nozzle Control Spring.
- E2: Condensation Pressure input (opening).
- E3: Liquid Booster Pump Pressure input (closure).

2.1.1. Air Inlet Duct

The Air Inlet Duct provides flow connection between the Air Intake of the Pod and the stator of the Ram Air Turbine in the Cooler.

The Air Intake operating parameters are:

- Total pressure recovery;
- Additional drag force.

Both parameters are within aircraft Manufacturer responsibility and, as single interface to the Cooler, the specified recovery efficiency of 90% of the dynamic head has been taken into account at any internal flow and the test rig is calibrated to deliver this value.

2.1.2. Ram Air Turbine

The Ram Air Turbine (RAT) is a single stage turbine, designed for high efficiency and driving the shaft of the refrigerant Compressor (vapor) and Booster Pump (liquid).

The RAT features an inlet vane stator and a rotor blade disc and exploits the pressure drop between the dynamic recovery pressure and the ambient. The stator acts also as a “barrier” for foreign objects entering in the Air Inlet duct, preventing damage to the other parts of the Cooler. The Compressor and the Booster Pump represent the energy input into the refrigerant vapor cycle and act as RAT brake in a very stable loop because:

- the RAT output power is in parabolic relationship with the rotation speed (increases and then decreases with rotation speed increase).
- the Compressor and the Booster Pump power absorption is geometrically proportional to the rotation speed (increases with rotation speed square).

The condensing and evaporation pressures deriving from the interaction of the refrigerant and air loops dictate the working point (RAT rotation speed, Fig. 2).

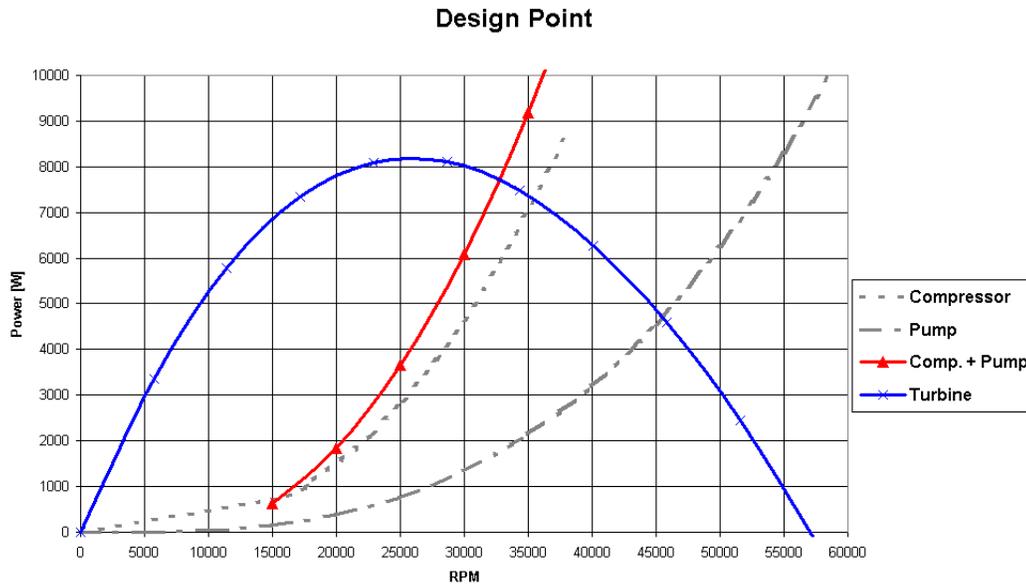


Figure 2: Design Point for RAT

For safety of operation, the RAT disc withstands the centrifugation effect (disc burst of the RAT) deriving from rotation speed, even in absence of shaft load or in case of shaft shear. The empirical analysis showed that the RAT can withstand rotation speeds over 40000 RPM without suffering any damage.

The high temperature, generated by the Compressor in the RAT hub and the Heat Exchanger at the flow discharge, prevents icing problems inside the Cooler, at any flight condition.

2.1.3. Refrigerant Condenser Heat Exchanger

The Refrigerant Condenser Heat Exchanger (RCHE) provides heat rejection from the Rankine vapor cycle into the airflow at the RAT outlet.

The power drained from the RAT causes beneficial temperature drop (decrease) in the airflow upstream of the RCHE.

The increase of the air temperature downstream of the RCHE, due to the heat rejection from the Cold Walls cooling, is directly connected to the amount of the airflow.

The condensing temperature (and consequently pressure) is affected by:

- Air recovery temperature, depending on static temperature and aircraft speed;
- Overall heat transfer (power to be dissipated) in the payload;
- Flooding of the Condenser refrigerant side, that reduces the “working” heat transfer surface.

2.1.4. Air flow control Louvers

The power generated by the RAT and the one absorbed by the refrigerant cycle need to be matched across the full flight envelope with necessary energy drained from the airflow.

This requires to account for:

- Simultaneous low altitude and high speed flight condition. The power of the RAT exceeding the need would cause over-speed and excessive power input in the refrigerant loop;
- Low temperature condition (Cold Walls overcooling);
- High altitude flight condition. The heat transfer becomes critical because of the low air density.

Discharge is across a Louver Valve that forms an Air Nozzle. The cross section of the Air Nozzle ranges from 10 to 45 cm².

The Louvers in the Valve rotate to reduce or increase the exit area of the air path, thus regulating the air mass flow through the Cooler. The Louvers withstand, by proper hinge position, the internal air pressure build-up in the specified flight conditions.

2.1.5. Louvers Hydraulic Actuator

Actuation of the Louvers is performed by push-pull of a small hydraulic cylinder (Louvers Actuator). The Spring inside the Actuator and aerodynamic loads keep the Louver Valve normally in closed position. A failsafe, completely hydro-mechanical device has been selected, whose major features are:

- Load threshold by Spring force at the minimum air flow section to provide positive shutting actuation against frictions and covering the refrigerant loss case (no load at the RAT shaft);
- Opening action caused by condensing pressure;
- Closing action caused by the pressure from the RAT driven liquid Booster Pump (RAT speed sensor).

The control stability is provided by:

- Condensation pressure build-up that increases Air Nozzle section, against the Spring force, at low speed/high temperature condition;
- Increase of the Booster Pump pressure at high RAT speed (high Mach/pressure ratios) decreases the Air Nozzle section, thus reducing the RAT power.

2.1.6. Air Nozzle Control Spring

In addition to the functions described in previous points, the Air Nozzle Control Spring offers a spring rate to ease equilibrium opening, as forces generated by condensation and Booster Pump pressures balance themselves.

2.1.7. Condensation pressure line input

The pressure in the condensing branch of the refrigerant circuit (P_{cnd}) forces the Air Nozzle opening through the actuator extension thrust section.

The condensing pressure, direct consequence of both the air stagnation temperature and the refrigerant heat rejection, represents the best signal for opening.

As discussed, the minimum P_{cnd} to open is defined by the threshold of the Air Nozzle spring. Complete opening is quickly reached (even at low RAT speed) due to rapid build-up of the pressure with temperature.

2.1.8. Liquid Booster Pump pressure input

The Booster Pump pressure, which increases with RAT speed, is employed as speed sensor and operates the retraction actuator thrust section, opposing to the one under the condensing pressure.

An increase of the RAT speed raises the Booster Pump pressure and involves progressive closure of the Air Nozzle in balance with the P_{cnd} . A smaller Air Nozzle reduces the liquid Booster Pump pressure and raises P_{cnd} . The increase of P_{cnd} causes the Air Nozzle to open, reacting to the liquid Booster Pump. The balance of Control Spring force plus extension force from P_{cnd} against retraction force from Liquid Booster Pump pressure is fully stable and provides Air Nozzle control over the flight envelope, performing an active speed control system.

3. REFRIGERANT VAPOUR CYCLE

3.1. CHARACTERISTICS OF THE MVX[®] COMPRESSOR

The Compressor employed in the Cooler is a two-stage machine with MVX[®] technology, a dynamic compressor (so-called “regenerative” or side-channel) featuring a pressure generation close to the one obtained from a volumetric unit. This represents the “core” of the Cooler. The Compressor is composed by a blade bearing rotary disc (rotor) and a stator forming a lateral channel where the centrifuged fluid is collected and repeatedly directed to the base of the rotor blades receiving a further impulse. The sum of impulses progressively increases the inlet fluid pressure, since the outlet is reached and the stator channel itself is interrupted to leave free passage to the blades only.

FIMAC has adapted the MVX[®] machines, used in industrial field to compress air, for the refrigerant operation. This required size reduction and multistage architecture, made possible by the understanding of the aerodynamic and thermodynamic behavior of the MVX[®] machines. The resulting pressure-flow characteristics is a good compromise between the Volumetric (large, heavy and low speed) and Centrifugal machines (very high speeds to reach required pressure ratio). For refrigerant operated, two-stage MVX[®] machines, the characteristic is a relationship between the Flow Parameter “ K_w ” and the Pressure Parameter “ K_q ”.

The above parameters can be defined as:

$$K_w = W_R/(\rho VA) \quad \text{and} \quad K_q = \Delta p/(1/2\rho_R V_P^2)$$

where:

- V_P : tip peripheral speed of the rotor
- A : cross section area of the lateral channel
- V : average peripheral speed of the blade row
- W_R : mass flow rate of the refrigerant fluid
- ρ_R : density of the refrigerant fluid
- Δp : pressure rise between compressor inlet and outlet

The characteristic is a straight line relationship of the type $K_w = C_1 - C_2 \times K_q$, where coefficients C_1 and C_2 depend on machine dimensions.

In the actual Cooler the characteristic equation is $K_w = 7-10 \times K_q$.

The MVX[®] Compressor design is a peculiar feature of this system being highly beneficial as:

- Capability of adjusting the mass flow and the delivery pressure at a given rotation speed without external control;
- Compatibility of operation with two stages in series without stall or other constraint;
- Internal routing of re-circulation flows (bearings and shaft seal cooling with liquid refrigerant adduction).

3.2. DESCRIPTION OF THE COMPONENTS

With reference to the Figure 1, the following significant components are highlighted:

- B1: MVX Compressor first stage (low pressure).
- B2: MVX Compressor second stage (high pressure).
- B3: Refrigerant Condenser Heat Exchanger (flooded zone).
- C1: Liquid Booster Pump.
- C2: Cold Walls refrigerant metering nozzles.
- C3: Cold Walls cooling (vapor generation).

3.2.1. MVX[®] Compressor first stage (low pressure)

The suction of the first stage of the Compressor receives the vaporized refrigerant directly from the Cold Walls return line and recovers also the internal flows from the bearings and the shaft seal cooling circuits. The refrigerant at the compressor inlet can be dry, i.e. fully evaporated, or have variable liquid title, i.e. wet to various stages of partial evaporation. The MVX[®] Compressor is compatible with liquid, enabling suction of wet vapor, with great simplification of the system.

Major parameters of the first stage of the Compressor are:

- The inlet pressure defines the Cold Plate evaporation temperature condition;
- The channel area is sized to accommodate the flow rate of the vapor cycle.

The first stage of the Compressor is obtained in the innermost side of the Compressor wheel. The RAT drives the shaft to which both the Compressor and Booster Pump wheels are fixed.

3.2.2. MVX[®] Compressor second stage (high pressure)

The second stage of the Compressor is directly fed from the low-pressure stage.

The working point results from the combination of the rotation speed, the operation of the Condenser cooled by the airflow and the low-pressure stage delivery condition.

3.2.3. Refrigerant Condenser Heat Exchanger (flooded zone)

In the Refrigerant Condenser Heat Exchanger, the airflow from the RAT cools the heated, compressed refrigerant vapor flow delivered by the Compressor, in a mixed cross-flow and counter current heat transfer arrangement.

The heat transfer basically happens in three steps:

- Overheated upper zone, that receives the refrigerant from the compressor outlet, with maximum heating of the air (above condensation temperature);
- Condensation intermediate zone;
- Flooding lower zone, where the refrigerant is cooled (sub-cooled) at a temperature lower than the condensation value.

The flooding of the lower portion of the Condenser (refrigerant overcooling) is the parameter acting on the refrigerant mass flow at the fixed area orifices of the Cold Walls.

The effects of the different levels of the Condenser flooding are:

- Increase of the available liquid phase pressure drop at the orifices, with consequent increase of the refrigerant mass flow and reduction of the Compressor pressure ratio;
- Reduction of refrigerant overheating at the Compressor outlet, due to the lower pressure ratio and higher efficiency working condition;
- Reduction of the Condenser effectiveness with increase of the condensation temperature;
- Raise of the evaporation temperature consequent to the increase of the condensation temperature and then lower pressure ratio of the Compressor.

The Condenser flooding causes the following effects on the air loop working point:

- Increase of condensing pressure, with opening effect on the Air Nozzle;
- Increase of the delivery pressure of the Booster Pump, with Air Nozzle closing effect;
- Increase of condensing temperature, that in turn causes significant increase of RAT power demand (braking effect) with reduction of the RAT rotation speed as end result.

3.2.4. Liquid Booster Pump

The Liquid Booster Pump is a RAT driven Impeller that provides pressure rise of the flow delivered at its outlet and directed to the orifices of the Cold Walls. Same as the Compressor, also the Liquid Booster Pump takes advantage of the MVX[®] technology.

The pressure boost generated in the Liquid Booster Pump is useful in winning the pressure drops of the liquid distribution pipe along the Cooling System. The obtained pressure margin has the same effect of the apparent pressure rise deriving from the refrigerant sub-cooling, avoiding premature boiling and enabling refrigerant metering and distribution at the Cold Walls orifices. Due to the presence of large amount of liquid inside the Cold Walls, their thermal level will remain within acceptable limits also during transients (attack angle or accelerations) that would otherwise cause insufficient supply of liquid refrigerant.

3.2.5. Cold Walls refrigerant metering nozzles

The refrigerant distribution and metering at the Cold Walls is ensured by the action of a number of parallel metering nozzles, located in the payload boxes all along the apparatus.

The metering nozzles provide, through an equivalent fixed area orifice, appropriate pressure reduction of the liquid refrigerant and fast injection in the evaporation galleries. Subsequent flow activation and progressive vapor generation is caused by the needle part of each metering nozzle. The vapor generated at the surface of the evaporation gallery is continuously ablated by centrifugal effect caused by the swirls along the needle.

4. ACTIVE REFRIGERANT CHARGE CONTROL

4.1. DESCRIPTION OF THE COMPONENTS

With reference to the Figure 1, the following significant components are highlighted:

- D1: Refrigerant Tank.
- D2: Electrically driven Pump.
- D3: Discharge flow control Valve.

4.2. OPERATION OF THE COMPONENTS

4.2.1. Refrigerant Tank

The functions of the Refrigerant Tank are:

- Dead volume compensation for hot conditions.
- Supply of liquid amounts to flood the Condenser in cold conditions.

Main design features concern the structural aspects (provision of volume for storage under high pressure) and obtaining the largest possible volume, as well as physical integration with the Electrical Pump and Valves bodies to minimize the occupied space.

The Reservoir Assembly performance, according to the requirements, consists in assuring that the fluid into the refrigerant circuit can move in the Refrigerant Tank when the operating conditions of the thermal cycle require less fluid into the circuit itself.

4.2.2. Electrically driven Pump

The Electrical Pump is a AC motor driven gear Pump having an on-off operation. It provides the trimming of the refrigerant circulating volume by pumping liquid into the circuit from the Tank when required by the operating conditions of the thermal cycle. The input signal is given by the Electronic Control Unit (ECU) which controls the thermal cycle working pressures.

The pump performance, according to the requirements, is to generate a flow of approximately 1 liter per minute against a pressure rise of about 500 kPa. The fluid is sucked from the Tank and sent to the high pressure line upstream the expansion nozzles.

4.2.3. Discharge flow control Valve

The unit is a normally closed, miniature solenoid valve. On-off operation of the Valve causes to dry the refrigerant circuit, moving the fluid into the refrigerant Tank when the operating

conditions of the thermal cycle require less fluid into the circuit itself. The input signal is given by the ECU (Electronic Control Unit) which controls the thermal cycle working pressures. The valve performance, according to the requirements, consist to open or close the high pressure line of the refrigerant circuit filling the Refrigerant Tank.

5. REGULATION PRINCIPLES

A wide level of self-adjusting operation of the Cooler has been a design target, to ensure integrity and independence from external power sources and other equipment.

Primary control is operated by the hydro-mechanical air outlet actuation that, as already discussed, is independent from external inputs, is fully stable and can easily cope with the ambient and flight conditions, maintaining the RAT rotation speed within design limits under different air speeds and environmental conditions (altitude, air density and static temperature).

A secondary, superimposed control is adopted to cope with the variation of the air temperatures and widen the tolerance to the refrigerant charge content variations.

This required the adoption of an electrically based regulation device and circuit. The regulation controller (ECU) operates this secondary loop trimming the active volume content of refrigerant. Inputs to the ECU are the signals from the transducers sensing the pressure of the Liquid Booster Pump delivery (P_{pump} signal) and of the evaporation (P_{evap} signal) lines.

The outputs are discrete, fixed time intervals of switching ON instructions to the Solenoid Valve or to the Electrical Pump.

Under low speed and “cold” operation, the thermodynamic cycle flattens and therefore the available pressure drop and flow rate at the Cold Walls metering nozzles reduce. To maintain the power subtraction capability, it is necessary to increase the circuit flooding so that liquid refrigerant can be pumped through a liquid circulation effect.

When the external conditions become “hot” or highly energetic, it is necessary to operate a true refrigerating cycle to obtain evaporation pressure as low as possible. The circuit is to be dried, by stowing refrigerant in the Tank. Drying the circuit, and namely the Condenser, improves the effectiveness of the thermal exchange surface. This reduces the condensing pressure, raises the Compressor pressure ratio and lowers the evaporation pressure (temperature) at the Cold Walls metering nozzles.

6. ELECTRONIC PROCESSOR ADDITIONAL TASKS

6.1. TASKS

In addition to the control of the amount of active refrigerant, the ECU performs the tasks of system start-up and of outputting alarm raise in case of malfunctions or flag of maintenance need.

6.2. START-UP PROCEDURE

Upon receipt of inputs from the System computer, the Cooler is ready to operate in its complete capabilities.

6.3. SIGNAL OUTPUT

The ECU provides the System computer with a codified BIT signal indicating that a fault/maintenance need has taken place in the Cooler.

7. CALCULATED PERFORMANCES, TEST ANALYSIS & RESULTS

7.1 PRINCIPLES

An initial set of calculated performances against all operational conditions was generated by means of a FIMAC mathematical model according to generally accepted aero-thermodynamics laws and proprietary calculus related to the operation of the involved machines.

Sets of development tests have been conducted in order to simulate several flight conditions on rig units. A pneumatic test rig has been designed and manufactured with the purpose to generate an airflow into the air path through the Cooler development unit.

The conditions experienced range over an input airflow at sea level conditions having a speed from 0.3 to 0.8 Mach and static air temperature from ambient temperature up to 50°C. Inserting liquid nitrogen into the air stream it was possible to qualitatively evaluate the Cooler behavior with static air temperatures down to -25°C.

The results emerging from the tests have been used to improve and validate the mathematical model, thus giving the necessary confidence for the performance calculation in the conditions not covered by the rig testing.

7.2 CORRELATION OF RIG TESTS

During development phase, many experimental tests have been conducted with Coolers fed by the rig, that have reproduced the operational performance conditions at sea level, which are very close to the worst case of high temperature. The operating conditions envisaged in the aircraft flight envelope, between 0.3 to 0.8 Mach, at sea level and throughout all air temperatures have been fully covered by the ground tests.

The main functional parameters measured during the experimental tests can be extended to other flight conditions if separately considered.

The total pressure P_T at the Cooler inlet on the rig is equivalent to total pressures collected at different altitudes (different P_{Amb}) and Mach numbers M according to the following equation:

$$P_T = P_{Amb} \cdot (1 + 0.2 \cdot M^2)^{3.5}$$

Likewise, the total temperatures T_{Tot} on the rig are equivalent to other conditions T_{Amb} :

$$T_{Tot} = T_{Amb} \cdot (1 + 0.2 \cdot M^2)$$

Eventually the same air pressure ratios β (i.e. total pressure at the Cooler inlet divided by ambient static pressure P_{Amb}) observed during the rig tests are found in other areas of the flight envelope:

$$\beta = \frac{P_{Amb} \cdot (1 + 0.2 \cdot M^2)^{3.5}}{P_{Amb}}$$

The rationale of this extension is to assess:

- The suitability of the operation of the Cooler from the viewpoint of mechanical stress and inlet power in the case of total pressure equivalence;
- The equivalence of the temperatures gives confidence, from the thermodynamic viewpoint, with respect to the refrigerant compressor operation;
- Same air pressure ratio means same inlet speed into the turbine wheel and equivalent turbine operating conditions.

It is rather evident that the above extension is affected by non-simultaneous occurrence of the parameters outlined, that would require a fully representative thermo-baric rig having a dramatic level of cost and power requirement.

Table 1 details the correlation between the results coming from the mathematical model and the output of the tests. Since correlation levels are very good (errors not higher than 2%) the validity of the mathematical model has been verified and used to reliably predict performances outside the rig testable field.

Test Number		1	2	3	4	5	6	7	8	9	10	11
Ambient Temperature [K]	Test value	317,8	310,9	312,3	313,4	321,0	321,5	318,4	322,9	239,7	243,1	262,0
	Model value	316,0	312,0	314,0	313,4	319,0	319,0	318,4	318,0	275,0	249,0	262,0
	Error [%]	0,566	-0,354	-0,544	0,000	0,623	0,778	0,000	1,517	-14,72	-2,427	0,000
RPM [x 1000]	Test value	23,010	16,934	10,939	19,355	28,120	32,400	15,000	30,912	28,359	19,269	18,161
	Model value	22,770	16,087	9,859	19,350	27,980	32,399	14,625	31,620	28,852	18,995	18,155
	Error [%]	1,026	5,002	9,873	0,026	0,498	0,003	2,500	-2,290	-1,738	1,422	0,033
Airflow Rate [kg/s]	Test value	0,355	0,299	0,178	0,298	0,432	0,521	0,233	0,505	0,513	0,317	0,288
	Model value	0,390	0,316	0,189	0,322	0,469	0,546	0,254	0,534	0,480	0,316	0,286
	Error [%]	-9,859	-5,686	-6,180	-8,054	-8,565	-4,798	-9,013	-5,743	6,433	0,315	0,694
Condensing Pressure [kPa]	Test value	422,0	337,00	266,00	344,00	571,00	725,00	321,00	701,00	289,00	76,00	79,00
	Model value	440,0	351,28	316,00	344,92	585,00	735,00	354,37	713,00	285,49	109,00	102,00
	Error [%]	-4,265	-4,237	-18,79	-0,270	-2,452	-1,379	-10,39	-1,712	1,212	-43,421	-29,114
Pump Pressure [kPa]	Test value	510,0	680,00	323,00	352,00	592,00	827,00	369,00	756,00	477,00	389,00	327,00
	Model value	499,4	416,00	332,00	385,71	647,00	801,00	378,00	771,00	493,00	344,00	307,90
	Error [%]	2,073	38,824	-2,786	-9,577	-9,291	3,144	-2,439	-1,984	-3,354	11,568	5,841
Evaporation Pressure [kPa]	Test value	217,00	227,00	236,00	202,00	221,00	247,00	234,00	241,00	110,00	73,00	87,00
	Model value	199,00	226,67	249,60	189,00	197,00	204,00	232,00	203,00	112,60	69,00	70,00
	Error [%]	8,295	0,142	-5,763	6,436	10,860	17,409	0,855	15,768	-2,364	5,479	19,540

Table 1. Model Validation

7.3 VALIDATION TESTS

In the following pages, the results of two tests performed on the Cooler and the connected System are shown. During the test run, a set of thermal sensors are placed on the Cold Walls to check the temperature levels of the payload boxes. Two more thermal sensors monitor the temperature of the refrigerant in the Cooler itself. The following Figure 3 provides a sketch of the Cold Walls arrangement and the position of the thermal sensors.

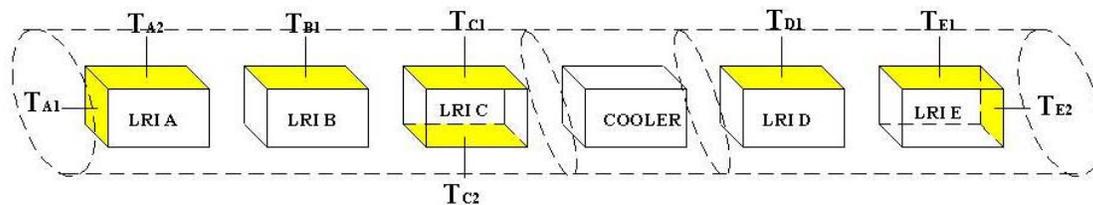


Figure 3: Thermal Sensors location on LRIs

Some other parameters are checked during the tests, to enable better confidence on the refrigerant cycle:

- The Air Speed at the ram air inlet;
- The rotation speed of the RAT;
- The mass flow of air circulating through the RAT;
- The pressure and the temperature of the refrigerant out of the Cooler (P_{Pump} and T_{OutCool});
- The pressure and the temperature of the refrigerant into the Cooler (P_{Evap} and T_{InCool});

7.3.1. First test

Figures 4 to 9 show one typical performance test on the Cooler in hot day ($49\text{ }^{\circ}\text{C } T_{\text{amb}}$) conditions, simulating Hi-Lo flight. The charge of refrigerant was of 1 kg. The test lasted about 1 hour.

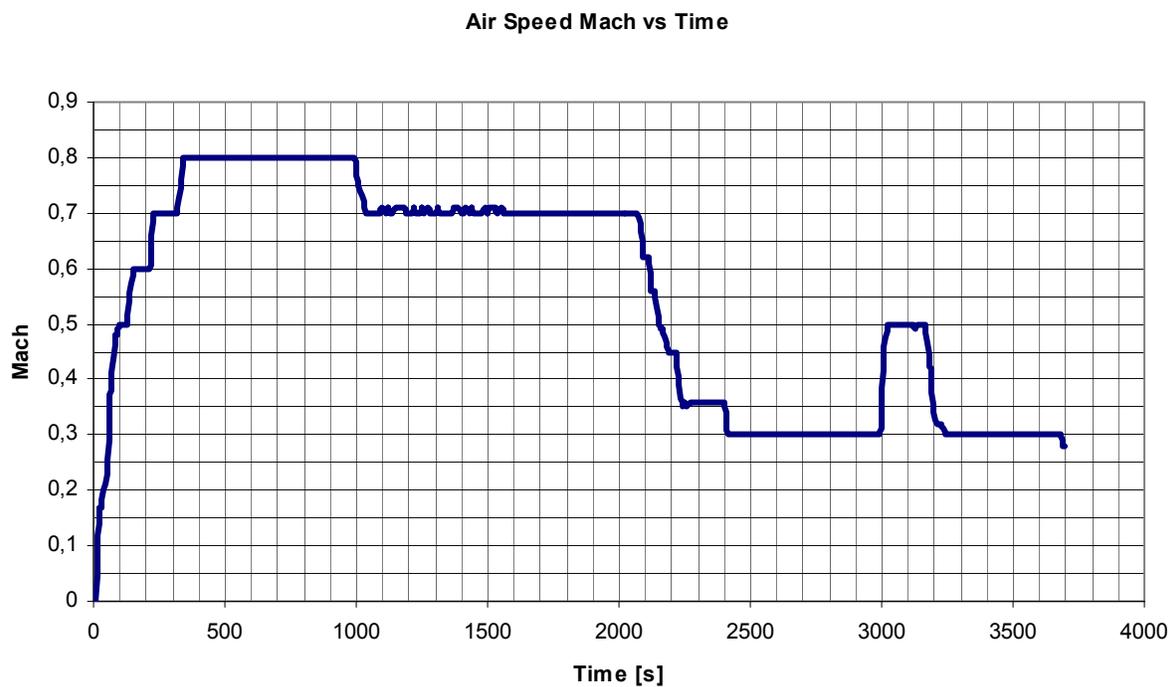


Figure 4: Mach number during the first test

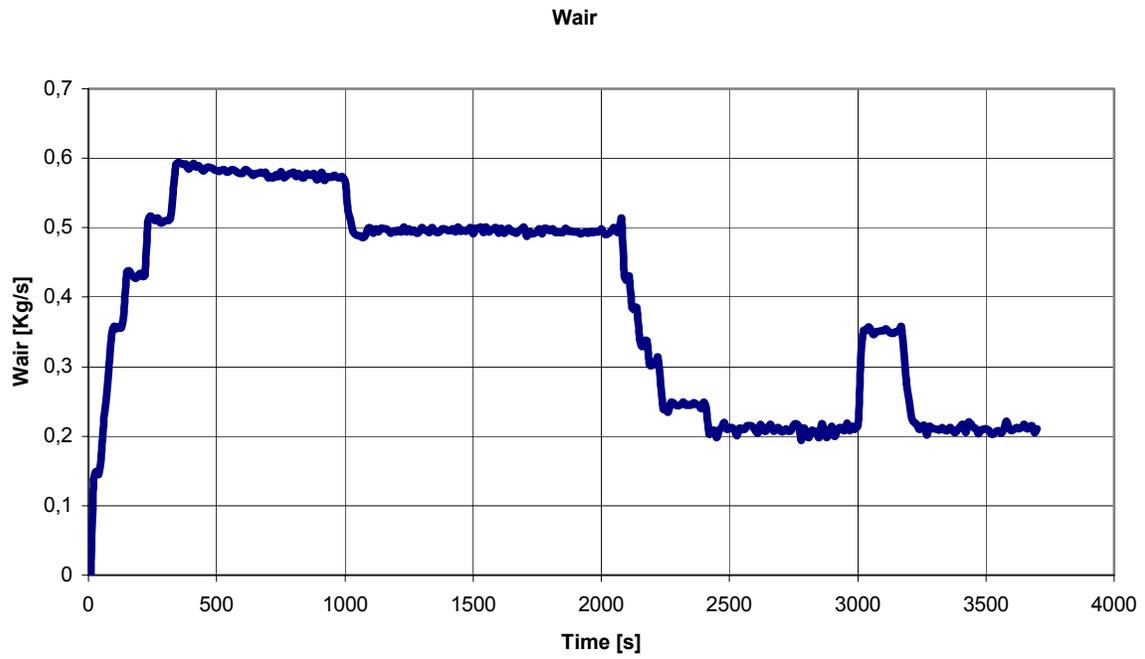


Figure 5: Mass of air circulating during the first test

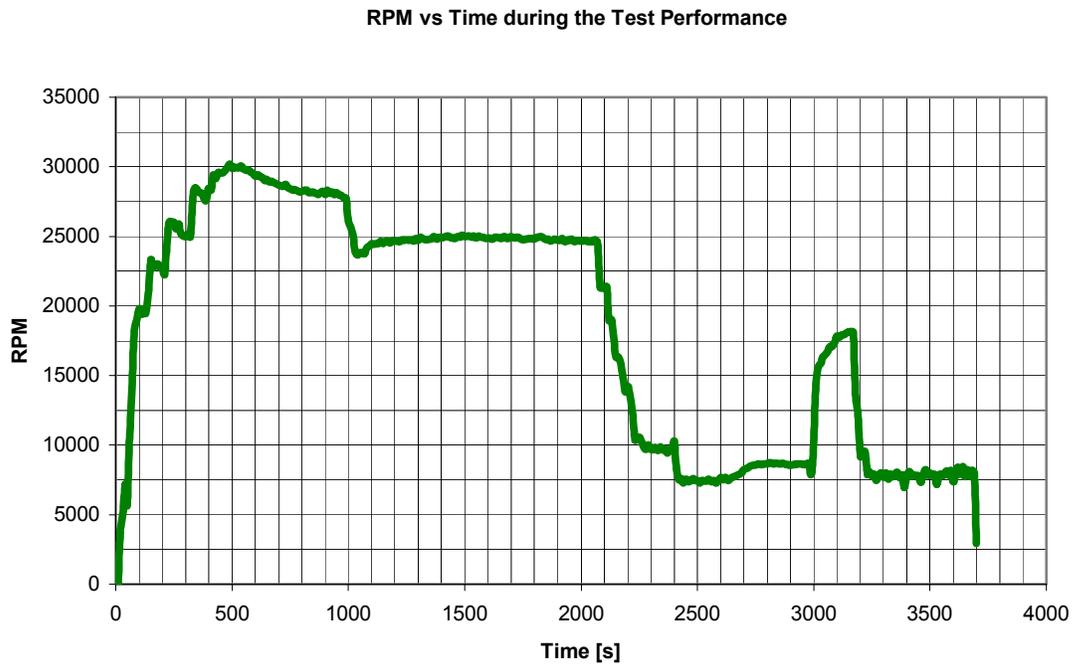


Figure 6: RPM during the first test

Refrigerant Pressure: Cooler Inlet and Outlet Pressure

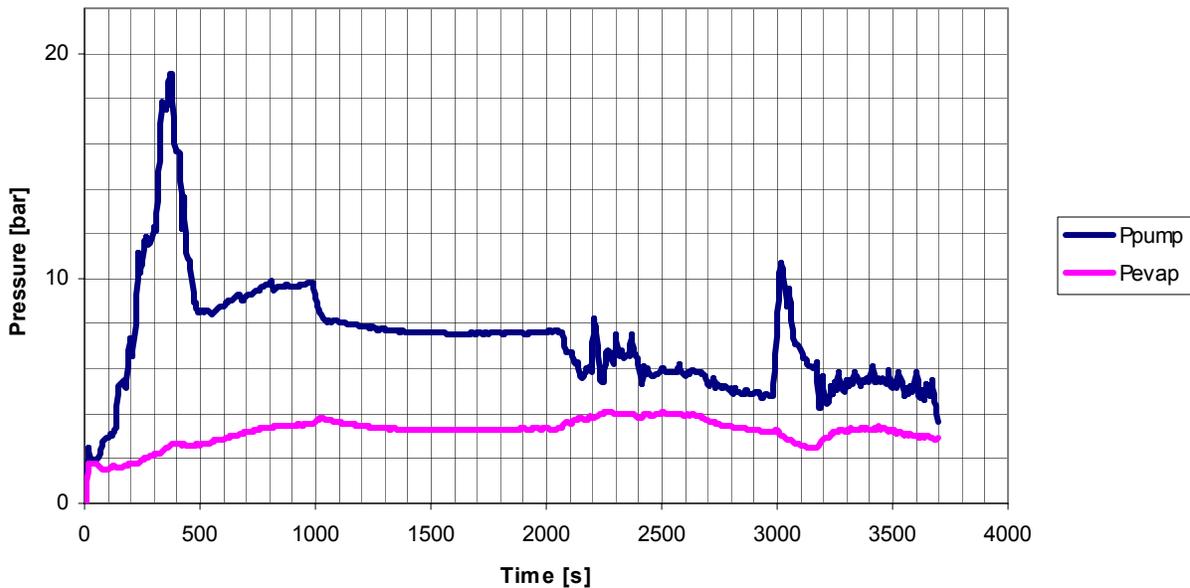


Figure 7: Pressure levels inside the Cooler during the first test

Refrigerant Temperature: Cooler Inlet and Outlet Temperature

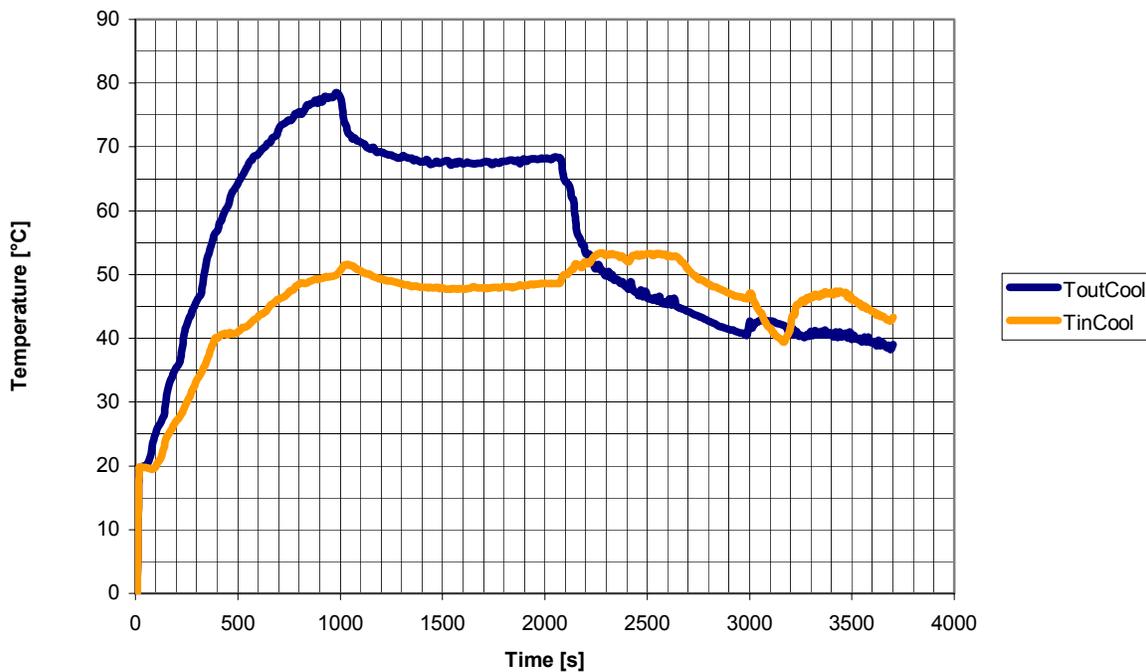


Figure 8: Temperature of the Refrigerant coming to and leaving from the Cooler during the first test

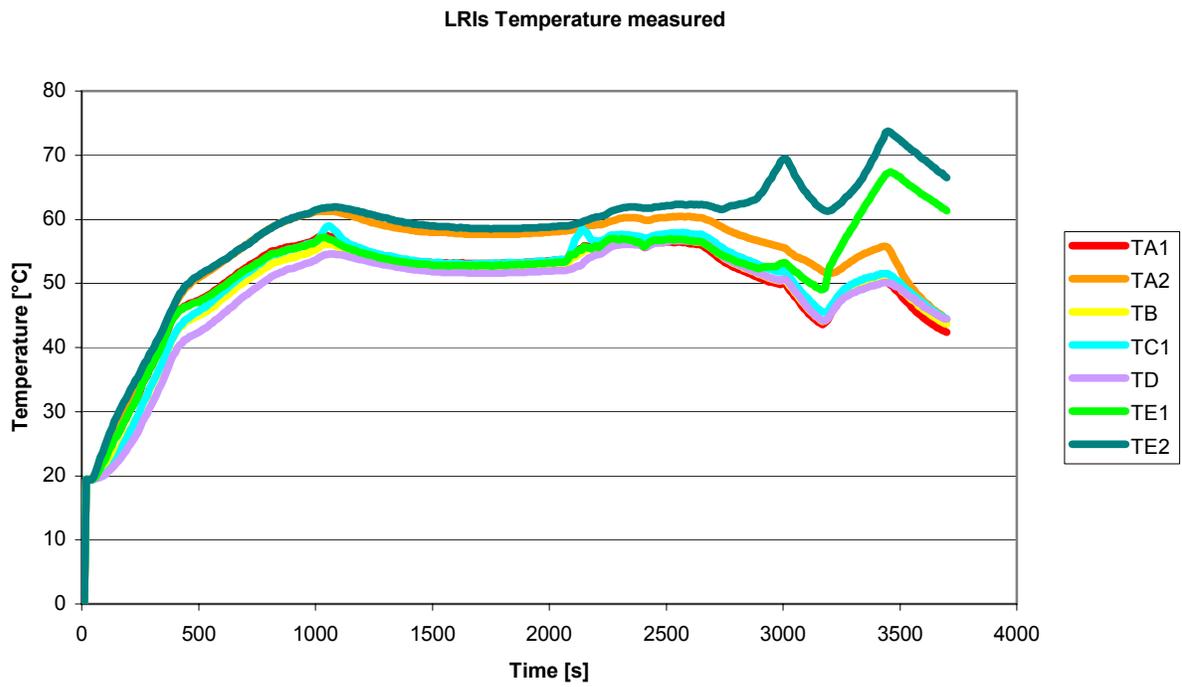


Figure 9: Temperature behavior of the cold walls during the first test

7.3.2 Second Test

Figure 10 to 15 show the result of another performance test, simulating Hi-Hi flight, again in hot day ($49\text{ }^{\circ}\text{C } T_{\text{amb}}$) conditions and with the same charge of refrigerant.

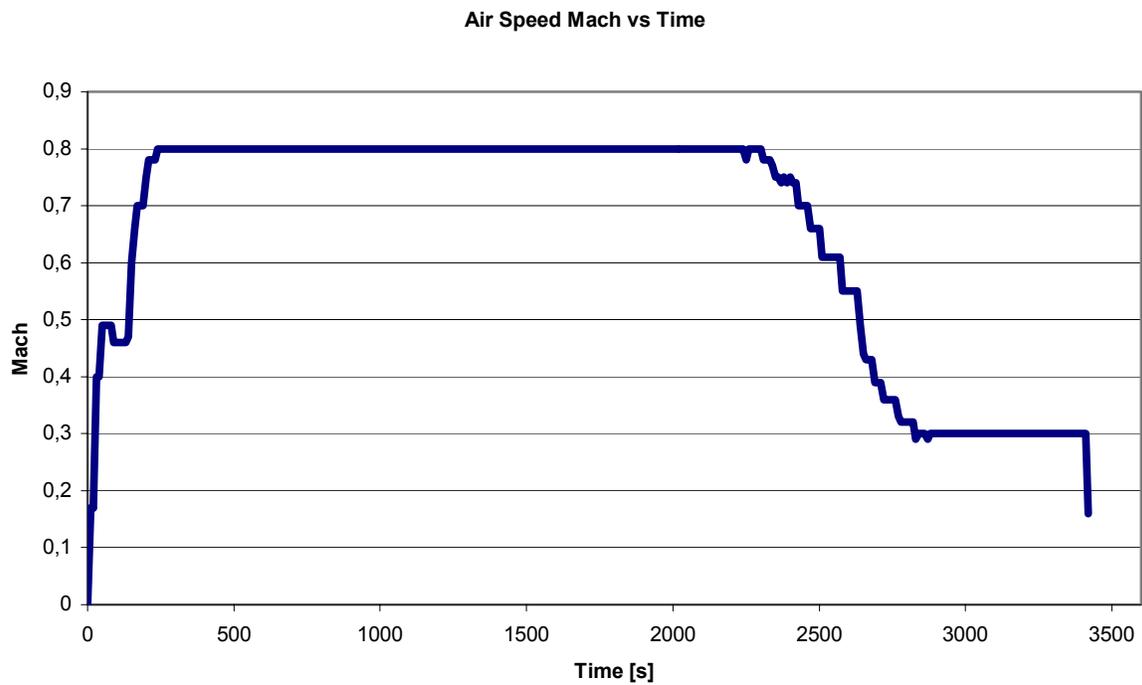


Figure 10: Mach number during the second test

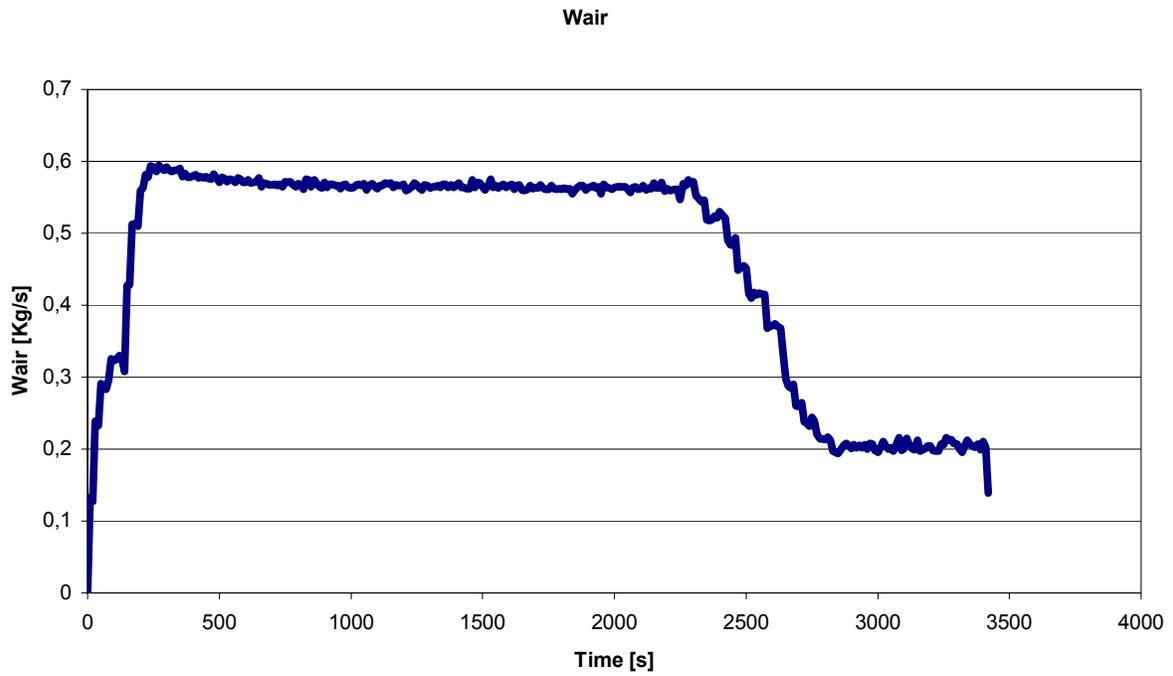


Figure 11: Mass of air circulating during the second test

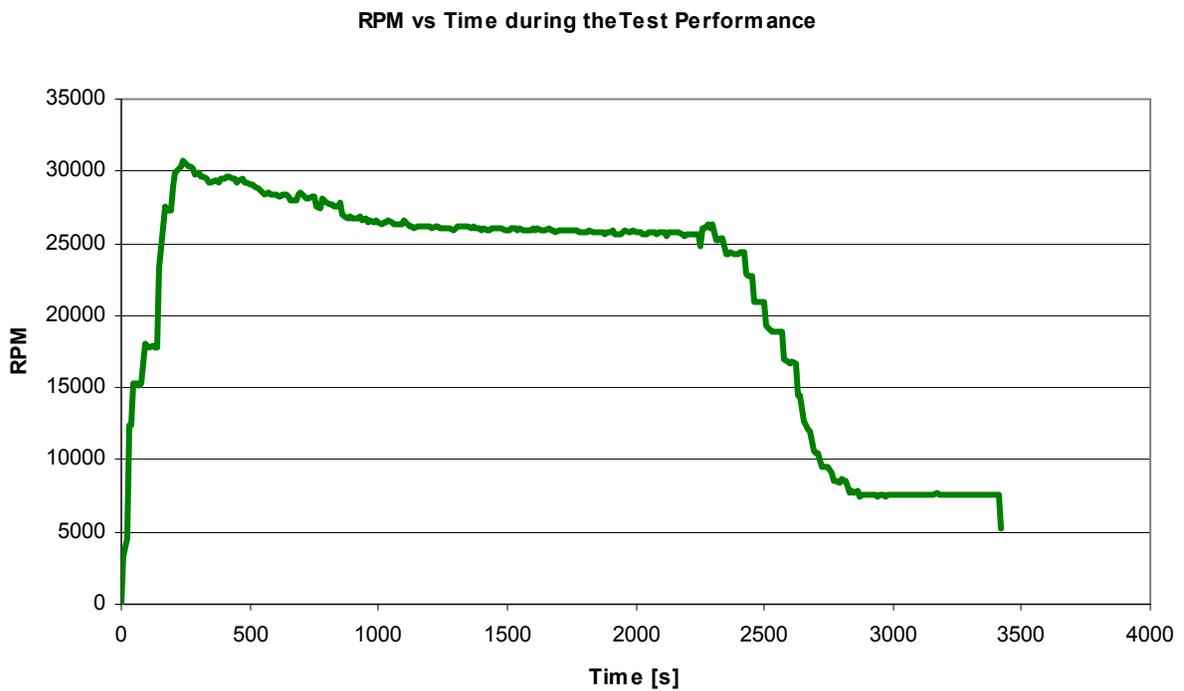


Figure 12: RPM during the second test

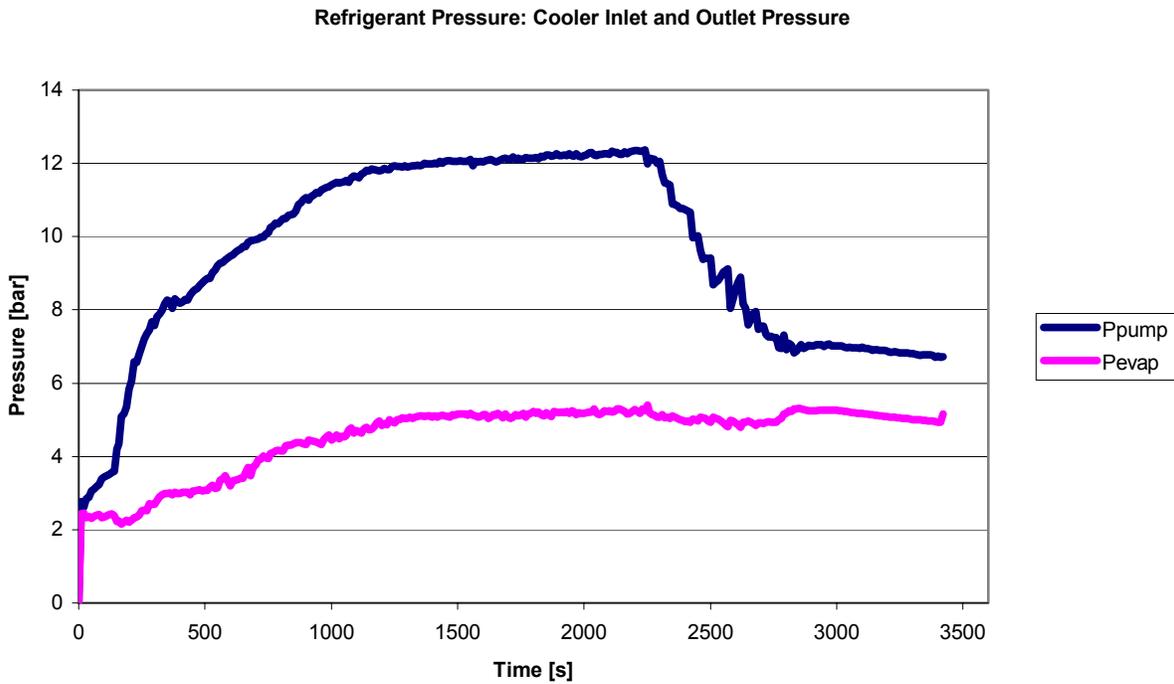


Figure 13: Pressure levels inside the Cooler during the second test

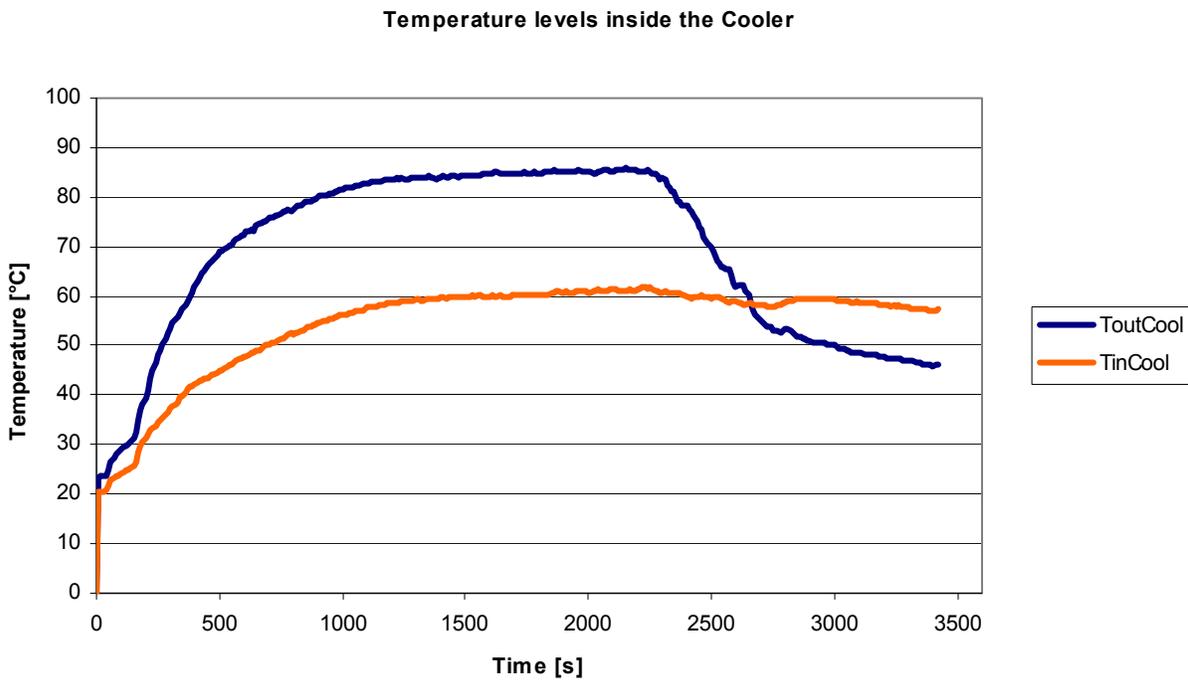


Figure 14: Temperature of the Refrigerant coming to and leaving from the Cooler during the second test

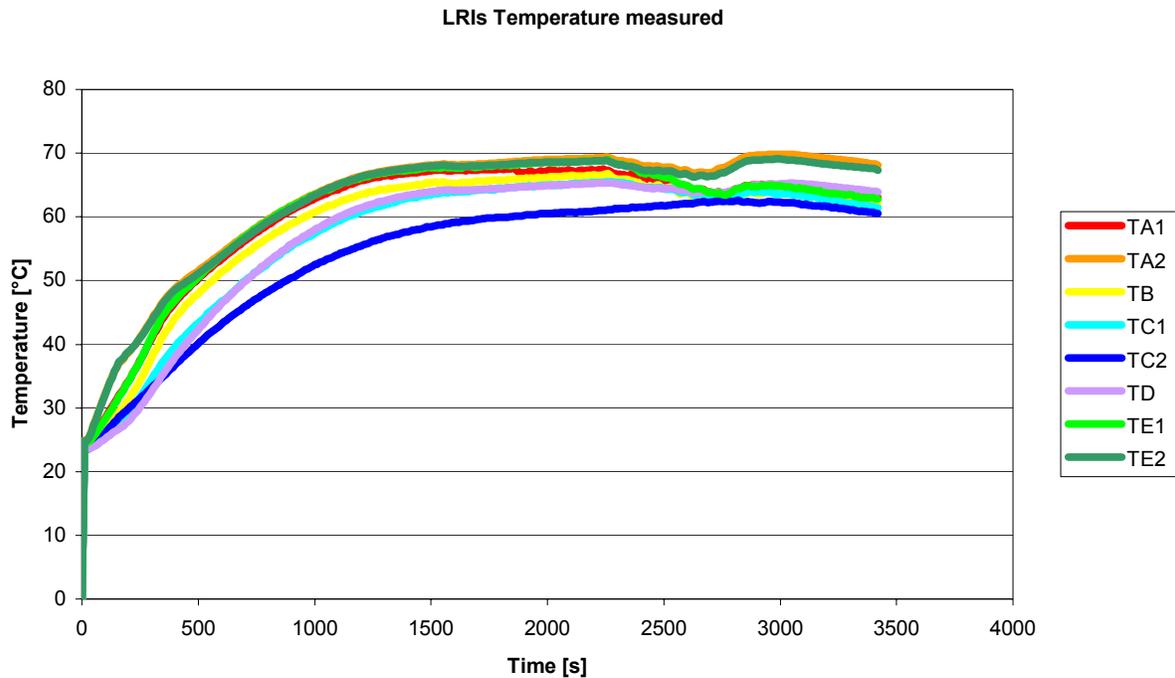


Figure 15: Temperature behavior of the Cold Walls during the second test

CONCLUSIONS

After almost 10 years of study, the Cooler is now in the production phase for a fighter plane and gives confidence about its performance. The over 1000 tests performed with success allowed FIMAC to look forward to improve the machine. At the moment, studies and preliminary tests are being conducted on a modified Cooler with a three-stage compressor.

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ACRONYMS

β	pressure ratio
ρ_R	density of the refrigerant fluid
Δp	pressure rise between compressor inlet and outlet
A	cross section area of the lateral channel
K_q	MVX Compressor pressure parameter
K_w	MVX Compressor flow parameter
LRI	Line Replaceable Item
M	Mach Number
MVX	Multivortex
P_{Amb}	Ambient pressure
P_{Cnd}	Pressure in the Condensing brench
P_{Pevap}	Evaporation pressure (Cooler return pressure)
P_{Pump}	Pump pressure (Cooler delivery pressure)
P_T	Total Pressure
RAT	Ram Air Turbine
RCHE	Refrigerant Condenser Heat Exchanger
RPM	Rotations per minute T_{Amb} Ambient Temperature
T_{InCool}	Temperature of the Refrigerant entering in the Cooler
$T_{OutCool}$	Temperature of the Refrigerant exiting from the Cooler
T_{Tot}	Total Temperature
V	average peripheral speed of the blade row
V_p	tip peripheral speed of the rotor
W_{AIR}	mass flow rate of air circulating through the RAT
W_R	mass flow rate of the refrigerant fluid