VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

HIGH ALTITUDE OPERATIONS WITH PISTON ENGINES POWERPLANT DESIGN OPTIMIZATION PART IV: RADIATORS OPTIMUM DESIGN

Luca Piancastelli, Leonardo Frizziero, Simone Pica and Giampiero Donnici
Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, Viale Risorgimento, Bologna, Italy
E-Mail: leonardo.frizziero@unibo.it

ABSTRACT

In high altitude operations, the cooling system takes part to the vehicle design optimization process. An integrated design of the cooling ducts is strictly necessary. At high altitudes, the cooling air is taken from high-pressure areas into an alternate, extremely optimized, path. A diffuser reduces the airspeed and increases pressure of the cooling air. Then a group of high performance finned radiators rejects the heat from coolant, air charge and oil. The high altitude, after diffuser radiator performance is discussed in this paper. At first high performance Formula 1 radiators are introduced and discussed. Experimental data are also exposed and summarized. The pressure drop and heat rejection are expressed in function or Re and Pr numbers of cooling air. Then the radiator performance at high altitude is extrapolated from the ground test data. Finally a few suggestions on radiator and cooling ducts arrangement are introduced.

Keywords: optimization, HALE, UAV, radiators, cooling, Meredith effect.

INTRODUCTION

Propulsion system of UAVs designed to fly subsonically >20,000m (65,000ft) for several hours requires very accurate design of the cooling system. In this flight regime, Turbochargers (TC), intercoolers and aftercoolers are needed to supply most of the intake pressurization required to compress the small air density into the engine. Volume flow requirements increase with altitude, which translates to larger TC size. Pressure ratio requirements also increase with altitude, which translates to more TC stages. Since power is proportional to airflow for any air breathing engine, the power plant size required to process airflow for a rated power will grow. High interstage and afterstage heat rejections are added to coolant and oil ones.

Because of the increased size and weight of the air handling system and thrust delivery components, a propulsion system optimized for high altitudes is significantly larger and heavier than its low altitude counterpart. Moreover, the HALE (High Altitude Long Endurance) vehicle needs more power to stay aloft. In fact, faster flight speeds are necessary to maintain dynamic pressure and support its weight in low-density air. Therefore, the propulsion system claims greater fractions of the airplane's gross weight. This runs counter to the airplane's ability to carry the necessary fuel weight and payload. The huge cooling system requirement supply energy for an additional thrusting device: the Meredith cooling duct. This is a subsonic ramjet engine that uses the heat dissipated by the main propulsion system for jet propulsion. This duct is composed by a diffuser, a radiator system that replaces the combustor and a nozzle. The third part of this paper introduced a simplified method for a preliminary design of the diffuser. In this fourth part of the paper, the radiators are introduced. A method for the preliminary design of this heat rejection system is discussed. At the end of the preliminary design CFD (Computational Fluid Dynamics) is necessary to optimize the Meredith duct.

In small piston engines, intake pressurized with two or three cascaded stages of turbocharging is a best choice for stratospheric aircrafts. This paper presents the radiator system and the duct optimization that is critical due to low air density. Unsurprisingly, much high altitude piston engine application failed to poor design of the installation. Powerplants and their cooling system have always been a problem. NACA people used extensively their wind tunnels and their knowledge to solve cooling problems even during the apogee of piston engines (WWII). Many papers come from that period to revive the knowledge of cooling that is periodically lost by the designers. This paper describes the solutions and the updates of this last 50 years of extensive work and optimization of automotive cooling systems. These updates can be directly applied to high altitude flying with a few corrections.

The mission

Since the fuel consumption follows a cubic low with speed, long endurance requires flying at reasonably low speeds. The dynamic pressure available limits the minimum speed to about 0.4M. A more likely speed will be between 0.6 and 0.85 M to avoid excessive wingspan and too low wing loading. In fact the aircraft should climb through the troposphere with its climatic problems to reach the calmer stratosphere.

Therefore, the aircraft will be more like a sailplane than a powered aircraft and will face handling problems at take off and lower altitudes. These problems will be amplified by the installation of radiators and cooling ducts.

THE COOLING CHALLENGE

The cooling drag of piston engines at high speed and altitude may make project fail if not properly handled. A radiator or finned barrel directly exposed in a free airstream will not achieve efficient cooling.

In fact, less than one third of the air arriving in front of the radiator will effectively flow across the core.

VOL. 11, NO. 9, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

The rest will flow around the obstacle, not without violent turbulence.

The efficiency is poor and the drag is prohibitive. A duct is then strictly necessary. In order to cool, air must flow through a radiator, with a mass flow easily determined by calculation. It is the pressure difference between the two faces of the radiator core, which forces air to flow through it. Without this pressure difference, no flow passes through the core and no cooling takes place. The drawback is that pressure drop implies higher pressure on the front face, and lower pressure on the rear face. The resulting rearward force corresponds to a drag. Therefore, cooling implies friction between the air and the radiator core walls, and pressure difference between the faces of the radiator.

The optimization process consists of cooling while minimizing the parasitic drag. It is always possible. In fact, it is difficult to cool an engine with minimal drag. Airplane designs often combine prohibitive drag with insufficient cooling.

High altitude cooling requirements

The Strato2C and Condor high altitude aerial vehicles demonstrated the feasibility of the concept and the high development costs of these solutions. Table-1 summarizes the cooling requirements of the Strato 2C powerplant,

Table-1. Strato 2C cooling system.

Coolers	LP air	IP air	HP air	Engine coolant	Engine+ Gearbox oil	LP oil	Total
# of radiators	2	2	1	1	1+1	1	9
Heat rejection (kW)	49	53	43	90	55	10	310
Efficiency (%)	74	72	69	64	86	86	-
Radiator Surface (m^2)	0.65	0.76	0.6	0.8	1.1	0.12	4

It is obvious that the enormous amount of cooling requires a design that transforms heat energy into thrust at least in cruise conditions. Cooling system optimization is then of paramount importance.

Radiators and cooling system design

In a common approximation, the heat transfer between the radiator core and the air is proportional to the air density, to the friction coefficient, to the mean air velocity across the fins (i.e. the volume flow), and to the temperature difference ΔT between the air and the fins or the liquid in the radiator.

The power needed for cooling is proportional to the square of the airspeed across the fins, and inversely proportional to the temperature difference ΔT between the air and the core or cylinder fins. It is independent of the density of air.

From this simplified theory convection cooling is economical only at low velocity, with temperature differences as high as possible.

A core with sufficient area (volume flow), an airstream considerably slower than the aircraft airspeed, and a high ΔT minimize the internal drag.

Therefore, it is advantageous to run the engine as hot as compatible with safe operating limitations. F1 racing engines had temperature of coolant up to 145 DEG C (290F) and lubricant temperature of 150 DEG C.

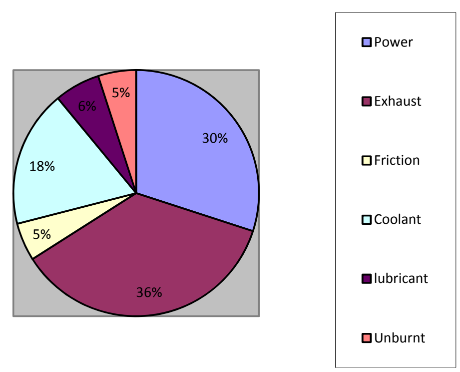

Figure-1. Power cooling naturally aspirated racing car.

This result is possible with pressurized systems that are prevalent in race applications. A pressurized cooling system utilizes an accumulator. This accumulator has a predetermined air room which acts as an air spring. It also incorporates the PRV (Pressure Relieve Valve) which is adjustable and substitutes the radiator cap.

The air spring allows the temperature expansion to compress the air without lifting the PRV. The PRV setting, the volume of the air spring, the coolant volume, and the amount of pressure added at ambient temperature determines the maximum coolant temperature allowed without opening the PRV.

Once the diffuser is designed with the outmost possible pressure increase and efficiency the radiator can be designed. It is convenient to adopt automotive racing heat exchanger cores.

Finned radiators

Many WWII radiators had a honeycomb matrix: it consists of an array of copper/brass hexagonal tubes, flared at the ends and tin soldered together (Figures 2 and 3). The air flows lengthwise through the tubes, whereas the coolant flows around them. This core is simple to build and offers the same wall area to the air and the liquid. This type of core can still be found in oil radiators in marine and industrial diesels and old jet/turboshaft engines. However, heat rejection optimization requires that the surface in contact with air should be considerably larger than that offered to the liquid.

Figure-2. Honeycomb radiator cores.

Figure-3. Hawker Hurricane MKII coolant radiator, the circular hole is for the oil radiator.

Therefore, modern radiator cores are of the finned flat tube type. The coolant flows in the tubes with fins to increase the air-side exchange area. End-tanks supply the coolant to the coolant tubes.

The Reynolds number in the air passages should be low for large heat transfer. The passage cross-section through fin should then be small.

Surface roughness in the passages increases the pressure drop but does not increase significantly the heat transfer. On the contrary, properly shaped fins improve convection.

Finned automotive radiators and air charge coolers (aftercoolers and intercoolers) are the most cost-effective, because of the existing technology base of mass produced automotive units that can be adapted to build a high altitude cooling system. Recent trends in automobile manufacturing tend to reduce weight, size and drag to improve fuel economy. Therefore, the new radiators have rendered the automotive technology base even more convenient for aircraft propulsion, to the extent that many manufacturers use automotive-derived heat-exchangers that are extremely weight competitive even in general aviation aero engine installations. The autoracing marketplace for turbocharged engines already includes a number of small business developers who mainly modify and assemble hardware manufactured by others. The cooling system is then cheaper because it is built up from mass produced components.

Automotive radiator sizing

A classical method for calculating car liquid radiator size comes from widespread knowledge of 1960's/1970's American car magazines. Several corrections were added through time. This method applies to spark ignition naturally aspired engines with an efficiency around 25%. For turbocharged CRDID (Common Rail Direct Injection Diesel) the equation also applies. The CRDID efficiency is 38% that is typical of Euro 3 or Euro 6 with SCR (Selective Catalytic Reduction) vehicles. For every cc of engine displacement add: 2 cc of core, 0.1 cc for (old) vertical flow radiator core, 0.1 cc for an in-line engine, 0.1/0.2/0.4 cc for a small/ medium/large trailer towing, 0.1 cc for a 2 row radiator, 0.2 cc for outside temperature (OAT) of 105°F (40.5°C), 0.2 cc for a small engine fitted to a heavy car (modern non sportive cars), 0.2 cc for a radiator fan area less than 78% of radiator frontal area, 0.3 cc for air conditioning, 0.3 cc for no fan shroud, 0.3 cc for a car with small enclosed engine compartment (modern cars), 0.5 cc for intercooler/aftercooler mounted in front of the liquid radiator. Then it is necessary to subtract: 0.1 cc for remote transmission cooler (not within radiator), 0.1 cc for standard in-line transmission, 0.1 for a single row radiator, 0.2 for a spacious open air engine compartment, 0.2cc for OAT less than 90°F (32.2°C), 0.4 for a large engine for performance car. For example, the VW Polo 1043cc radiator (1983-1990) perfectly fits. In fact, the core of the Polo radiator is 4,000cc and the method outputs 3,963cc (in-line engine, large trailer towing, two row radiator, OAT of 40.5°C, small engine-heavy car, small radiator fan area, air conditioning, small enclosed engine compartment). The method applies also for 1211cc Rotax 912 "standard radiator" that has a core of 2178 cc. In this case, the factors of high OAT, spacious engine compartment and the large performance car were considered. The Rotax radiator proved to be too large for a "high performance" application on a "sporty" ultralight aircraft and well design cooling duct. In this case the radiator is reduced by 36% (1323cc). The reason can be seen in Figure-4.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

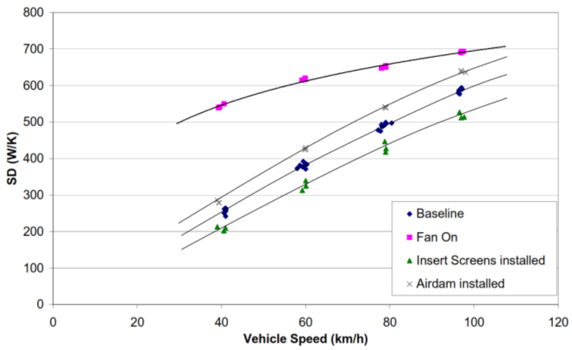

Figure-4. Influence of external elements on radiator performance [1].

Typically, the "design speed" of an automotive radiator is 40 mph (62 km/h) with the engine near the maximum torque and the fan not activated. The Take-Off velocity of an ultralight aircraft is 15 knots more than the stall velocity. The maximum stall velocity is 65 km/h. The minimum TO velocity is then about 90km/h. From Figure-5 the installed automotive radiator at 62 km/h has an SD of 310. The same radiator at 100km/h in baseline configuration has an SD of 540. So the ultralight aircraft can theoretically use a radiator that is 310/540=0.57 or 43% smaller in volume than a car. However, since the aircraft acceleration during TO is not instantaneous, the radiator volume reduction is inferior. Moreover, a slight over-dimensioning is necessary for low-speed/max-rate climb. Therefore, the cooling power is increased by 15%. In this case the aircraft reduction is expressed by equation (1).

$$V_{aircraft} = V_{automotive} f_{reduction} f_{climb} \Rightarrow$$
$$f_{reduction} f_{climb} = 0.57 * 1.15 = 0.65 \tag{1}$$

From these considerations the aircraft radiator is reduced by 35%. SD is a very common way to assess the cooling radiator performance. SD testing can be conducted under both stable and slowly changing operating conditions and is relatively insensitive to changes in ambient and coolant temperatures. SD can be expressed in terms of the heat exchanger effectiveness ε which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer rate. The maximum possible transfer rate C is always referred to the air-side heat capacity rate (i.e. equal to the air mass flow rate multiply by the specific heat of air) (3). The radiator Specific Dissipation (SD) is defined by equations (2) and (3).

$$SD = \frac{m_c c_{pc}(T_{ci} - T_{co})}{(T_{ci} - T_{ai})} = \frac{m_a c_{pa}(T_{ai} - T_{ao})}{(T_{ci} - T_{ai})} = \varepsilon \times m_a c_{pa} \tag{2}$$

Where ε is the heat exchanger effectiveness.

$$SD = \varepsilon C = m_a c_{pa} \varepsilon = \frac{Q}{T_{ci} - T_{ai}} \tag{3}$$

Alternatively, SD is defined as the heat dissipation rate of a radiator divided by the overall temperature difference across the radiator (5). SD is relatively insensitive to changes in ambient and coolant temperatures and the tests are conducted under both stable and slowly changing vehicle operating conditions. The specific SD (SD_s) is the SD for each unit of radiator frontal surface. SD depends on air velocity and water velocity. In racing radiators the coolant velocity is the maximum possible to keep the flow laminar.

Tuning

The main source of heat in a power generation system comes from the power the engine is producing. This paper considers only optimally tuned engines. In fact an un-tuned engine can place a massive load on the cooling system even outputting less power. Advanced/retarded timing and lean air/fuel mixtures will require more cooling system than a properly timed engine. Also, restrictive exhausts or improper valve timing may have the same effect. When considering the radiator heat-rejection capacity requirement, the engine output that you are using continually must be examined, not the maximum amount of power the engine can produce. This is typically the case of sporty high-power bikes or cars engines that will have undersized cooling systems (radiators or fins), when used in aircraft applications. Even in many aircraft applications, the full power-low speed cooling capacity only needs to be enough to cool the engine while idling and the few seconds of ground run.

Radiator selection

Copper and Brass radiators were used for many years in aircrafts and race application. Aluminium alloy is now the preferred material. In fact, copper have a higher thermal conductivity than aluminium. Unfortunately, the copper fins are paired with a brass tube and lead solder. The poor conductivity of lead solder reduces the heat transfer rate from the tubes to the copper fins. On the contrary aluminium alloy core is brazed. Therefore, the tube and fin are of the same material and are brazed into one thermally homogenous part. In addition, the aluminium core weighs 30% of an equivalent copper/brass core. Finally, customizing these radiators with TIG welding is easier and more readily achieved. Radiator thickness to frontal surface area and fin/tubes density and geometry are subject of continuous optimization. Racing radiators are becoming substantially thinner than in years past.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

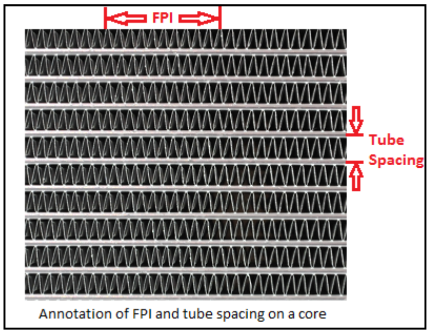

Figure-5. FPI and tube spacing.

In fact, doubling a radiator's available frontal surface area doubles the available heat rejection, while doubling the thickness of a core does not.

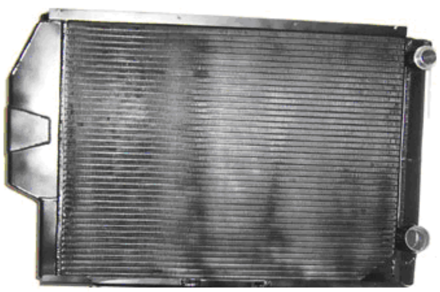

Figure-6. Formula 1 double pass radiator.

Fin pitch (Fins Per Inch-FPI) and tube spacing are fundamental parameters for core heat rejection and air side drag. FPI increase and tube spaces reduction increases surface area and heat rejection but increases also air-side drag. Tube spacing decreases also water-side pressure drop through the core. Top automotive applications keep the FPI around 15-18, while racing application currently arrive at 25 FPI. Not professional off-road applications tend to loosen the fin pitch down to 12 to allow dirt and mud to pass through the core. However, it is far better to use a proper grill to block any debris instead of less FPI. Tube spacing and geometry has less of an impact that FPI on the air-side efficiency of the core. In general, closer tube spacing withstands the higher pressures that are necessary for high altitude flight. Old single-pass radiator had an inlet and outlet on opposite tanks and no internal baffles. In this way the water passes through the radiator once. There were two styles of single pass radiators, down flow and cross flow. Crossflow (horizontal) radiators have the end tanks on the left and on the right, while the old-fashioned downflow (vertical) radiator had end tanks on the top and bottom. The double pass radiator has a baffle in between, so that the water must pass through the radiator twice in this configuration. Therefore, the inlet and outlet are located on the same side. Finally, there are radiators in which the water passes through the core three times. The inlet and outlet are on opposing corners, with two baffles, one in each tank. The triple pass radiators are rarely used because they have a high pressure drop on the water side. In double passing radiators the core's tube length is effectively doubled and the height is cut in half. Water-side backpressure is also increased. Typically going from a single pass to a double pass radiator the heat transfer capability increases of approximately 7%. This achievement has virtually eliminated single pass radiators for racing applications.

Tubes and fins can have many different shapes. Cooling tanks shape optimization is another very common issue in radiator design. With polymeric tanks, their shape is highly variable without adding cost or varying the core shape. The most common are the oval flat tubes. However, also other shapes are available: oval, flat, ovoidal, rounded rectangular, B-shapes, airfoil. Fins are usually multi louvered fins that are carefully and precisely aligned to maximize airflow and may have additional design features to improve turbulence.

Pressure drop

A pressure drop of a modern Formula 1 racing radiator is given by equations (4) and (5). This cross-flow, double-pass radiator has a 1.35" (27mm) thick core with 25 FPI.

$$\Delta p = k_L \operatorname{Re}^{1.6637} \tag{4}$$

$$k_L = 0.1097 \tag{5}$$

For radiators the Reynolds number is calculated with the radiator fin pitch as characteristic length (6).

$$\operatorname{Re} = \frac{p_{rad} \rho v}{\mu} \tag{6}$$

In this case p_{rad}≈0.0011 (25 FPI).

If the thickness of the radiator is increased equation (4) becomes (5):

$$\Delta p = k_L \operatorname{Re}^{1.6637} \left(\frac{s}{s_0} \right)^{1.33} \tag{7}$$

With s0=27mm. The use of the Reynolds number instead of the velocity solves many of the design problems due to the thinner air at 20,000m. The pressure drop depends mainly of the FPI parameter, and, for this reason, it is similar for topmost quality radiators.

Heat rejection

In general Q is expressed by equation (8).

$$Q = \alpha (T_{ci} - T_{ai}) S \tag{8}$$

But the overall external (air) heat transfer coefficient α depends on Re, Pr and on the radiator geometry (8). It is then possible to express α in function of Re and Pr numbers for a defined radiator core.

ARPN Journal of Engineering and Applied Sciences

$$\alpha = \frac{1}{\mathrm{Pr}^{2/3}} f(\mathrm{Re}, core geometry) \tag{9}$$

The Pr number is (10)

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{10}$$

Both viscosity μ and thermal conductivity k depend on temperature, while C_p is nearly constant. The dependence from pressure is negligible. For viscosity μ, the Sunderland's equation is a good approximation (11):

$$\mu = \mu_0 \frac{T_0 + C}{T + C}\left(\frac{T}{T_0}\right)^{\frac{3}{2}} \tag{11}$$

In standard air T_0=291.5, μ_0=18.27x10^{-6} and C=120 are valid values. For k a valid interpolating polynomial is (12)

$$\mathrm{k} = -3.68312 \times 10^{-8}\,(-2682.25 + \mathrm{T})\,(-1.4221 + \mathrm{T}) \tag{12}$$

It is then convenient to write equation (7) as a function of Pr and Re numbers. The global heat transfer coefficient for the radiator of equation (4) is then (13)

$$\alpha = \frac{-1.619\mathrm{E}-5\mathrm{Re}^2 + 0.018\mathrm{Re} + 0.877}{\mathrm{Pr}^{2/3}} \tag{13}$$

Equation (13) holds for Re ϵ {180,580} and air velocity between 3 and 9 m/s. The design point is Re=350, Pr=0.72 and v=5.5 m/s. Air side is the most critical side of the radiator. Increasing the thickness of the radiator will increase the global heat transfer coefficient in a non proportional way (14).

$$\alpha = \frac{-1.619\mathrm{E}-5\mathrm{Re}^2 + 0.018\mathrm{Re} + 0.877}{\mathrm{Pr}^{2/3}}\left(\frac{s}{s_0}\right)^{0.88} \tag{14}$$

Coolant flow

As velocity increases, so does the coolant turbulation. The turbulence increases the heat rejection. Coolant flow rate and core size are optimized to compromise maximum heat rejection with pressure drop and power requirement.

Static pressure throughout the system drops due to different restrictions at each location in the system. Therefore, system pressure is higher before the core and lower afterwards. These pressure differentials also happen throughout the engine due to the changes in water passage cross section. The cylinder head is the location that needs the highest pressures to reduce boiling risks. Maximizing system pressure will then reduce risks of detonation in spark ignition engines. High system pressure reduces also head maximum temperature and fatigue due to low pressure spots.

The radiator in the Meredith cooling duct

In the case of A_B=1, A_i/A_B=0.35, ε=0.01 and circular duct (D=Dh) the results of Table-1 comes from Pellegrini's method (see part III of this paper).

Table-2. Exit data for a streamline diffuser at 20,000ISA+16.5DEG C (Hot Day -40 DEG C true temp.).

V_i (Mach)	0.4	0.7	0.9
p_B[Pa]	5816	6788	8043
T_B[K]	232	234	241
ρ_B[Pa]	0.088	0.1	0.116
V_B[m/s]	40	61	68
η	0.96	0.95	0.96
r	1.06	1.24	1.47

For v_i=0.4 Mach we have the following results: Re=235, k=0.02, μ=1.51E-5, Pr=0.73. These data are not far away from the radiator design point. In fact, the Re number is similar to ground applications. This is due to air velocity V_B=40 that is an order of magnitude larger than the design velocity of the radiator at sea level.

Therefore, the Formula 1 radiators perform well even at high altitudes. The pressure drop is 97 Pa. This value seems to be low but it is about 30% the pressure recovery of the diffuser. This is unacceptable for an efficient Meredith duct. Thinner radiators should then be used. In fact, the P51 Mustang experience demonstrated that it is convenient to have a single duct with increasing radiator temperatures. In fact, the P51D had two ducts for the main liquid cooler and the oil cooler, while the P51H had a single duct with the after cooler-oil (front) and the liquid radiator (back) stacked together. In our case we have at least three different temperature levels: the after cooler (about 120 DEG C), the coolant (140 DEG C), and the oil (150 DEG C). It is convenient to stack the three radiators together in order to achieve the maximum possible air temperature after the radiator.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

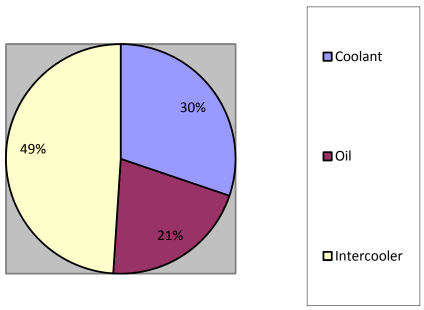

Figure-7. Strato2C cooling system. Heat rejected by the radiator groups.

If the heat rejection is the one of the strato2C, the relative radiator thicknesses of the cooling pack will be given by equation (15)

$$thk = th_{air} + th_{coolant} + th_{oil} \quad (15)$$

The total thickness *thk i*s a design choice that derives from maximum admissible pressure drop. Optimally and theoretically, it should not exceed 1/3 of the diffuser pressure recovery. In this way the Meredith thrust is optimized. In the hypothesis fo a single air charge radiator (aftercooler only), the unknowns are the radiator surface *S*, the air, coolant and oil radiator thicknesses. The evaluation of these unknown requires an iterative process. In fact the coolant and oil radiator are cooled by air with different temperature, pressure and velocity than the air charge radiator (16)-(25).

$$\Delta T_{air} = T_{air} - T_B \quad (16)$$

$$Q_{air} = \alpha(\mathrm{Re}_{diffuser}, \mathrm{Pr}_{diffuser}, th_{air})\Delta T_{air} S \quad (17)$$

The cooling air is heated up to $T_{air\_coolant}$ temperature and slowed down to $v_{afteraircooler}$ velocity. The Pr and Re number of the air cooling the coolant radiator are also evaluated (18)-(22).

$$\Delta T_{add\_by\_air} = \frac{Q_{air}}{C_p v_B \rho_B S} \quad (18)$$

$$T_{air\_coolant} = T_B + \Delta T_{addbyair} \quad (19)$$

$$p_{coolant} = p_B + \Delta p_{air} \quad (20)$$

$$\rho_{coolant} = \frac{p_{coolant}}{T_{air\_coolant} R} \quad (21)$$

$$v_{afteraircooler} = v_{coolant} = \frac{v_B \rho_B}{\rho_{coolant}} \quad (22)$$

$$\Delta T_{coolant} = T_{coolant} - T_{air\_coolant} \quad (23)$$

The thickness of the coolant radiator can then be evaluated (24).

$$Q_{coolant} = \alpha(\mathrm{Re}_{coolant}, \mathrm{Pr}_{coolant}, th_{coolant})\Delta T_{coolant} S \quad (24)$$

This process is repeated also for the oil radiator and is iterated after the right combination of surface S and total pressure drop is reached. The thicknesses of the air, coolant and oil radiator can then be evaluated. Results for the cooling duct of part III and various aircraft speeds (Mach) are summarized in Table-3. In Table-3 the maximum temperature to be cooled is 89 DEG C. This is the nominal temperature for a car powerplant that does not have the oil cooler. Therefore, the values calculated in Table-3 are the minimum ones. In fact, the maximum oil temperature for a racing car lubricant can be as high as 150 DEG C. This temperature has a very large influence of Meredith's duct thrust.

Table-3. Exit air data from the radiator (station 3) for various duct inlet airspeed (Mach) (see Table-2).

V_i (Mach)	0.4	0.7	0.9
T_3[K]	411	372	352
p_3[K]	5725	6570	7721
ρ_3[kg/m^3]	0.48	0.06	0.08
V_3[m/s]	72	99	103
p_loss[%]	26	16	12

The pressure loss p_loss factor is expressed by equation (25).

$$p\_loss = \left(1 - \frac{(p_3 - p_0)}{p_B - p_0}\right)100 \quad (25)$$

Fuel heating

A well known problem in flight is icing. It happens on wings, cowlings, propellers, fins and probes and also in filters and valves. The icing of the external parts of the aircraft it typical of the climbing to the stratosphere and to the descent phase, while the internal fuel icing takes place during the whole flight.

The availability of heating energy should be not overseen. Rolls Royce Trent engines use the oil cooling to heat the fuel. In the same way it is possible to use the cooling system of the engine to heat the fuel and the external surfaces of the aircraft. The fuel is also a heat sink for the aerial vehicle. In fact, during the climb phase, where speed is low and the power output is at its

ARPN Journal of Engineering and Applied Sciences

maximum, the fuel tanks are full. It is easy to add liquid-to-liquid heat exchangers in strategic points of the aircraft to dissipate energy or to increase fuel temperature. These exchangers are small, lightweight and readily available. They are already used for oil-coolant heat exchange. It is also possible to use heated fuel to prevent icing on external parts. For example, in the design phase it is possible to design integral aluminium alloy fuel tanks on wing leading edge.

Take off

During the take off engine thermal shock may take place due to sudden opening of the thermostatic valve. For this reason thermostatic valves are not common in spark-ignition aircraft engines. However, in high altitude aircraft overcooling may take place. A system to close part of the radiators should then be devised.

Idling

When the engine is idling during taxiing or waiting for the take-off clearance, the cooling system may overheat. This is common in spark ignition engines. For this reason fans are used in liquid cooling engines. These fans are highly detrimental of Meredith duct efficiency due to increased drag in cruise. For this reason it is better to use the fuel heat sink for this purpose. Diesel engine faces the overcooling problem. For this reason it is strictly necessary to use a thermostatic valve in CRDIDs (Common Rail Direct Injection Diesel).

CONCLUSIONS

In high altitude operations, the cooling system takes a very important part to the vehicle design optimization process. An integrated design of the cooling ducts is strictly necessary to convert the wasted energy into additional thrust. At high altitudes, the cooling air is taken from high-pressure areas of the aerial vehicle into an alternate, extremely optimized, path. A diffuser reduces the airspeed and increases pressure of the cooling air. Then a group of high performance finned radiators rejects the heat from coolant, air charge and oil. The high altitude radiator performance is discussed in this paper. The radiators are always placed in the Meredith duct after the diffuser. At first, high performance Formula 1 radiators are introduced and discussed. Experimental data are also exposed and summarized. The pressure drop and heat rejection are expressed in function or Re and Pr numbers of cooling air. Then the radiator performance at high altitude is extrapolated from the ground test data. Finally a few suggestions on radiator and cooling ducts arrangement are introduced. A correct radiator sizing makes it possible to obtain a positive thrust from the cooling system.

REFERENCES

[1] Wolfer H. Ignition Lag in Diesel Engines VDI-Forchungsheft 392, 1938, (English Translation, RAE Farnborough, Lib. No 359, UDC 621-436 - 047, Ig5g).

[2] E Mancaruso, S. S. Merola, B. M. Vaglieco. 2008. Study of the multi-injection combustion process in a transparent direct injection common rail diesel engine by means of optical techniques. International Journal of Engine Research (Impact Factor: 0.52). 01/2008; 9(6):483-498. DOI: 10.1243/14680874JER01308.

[3] H. Bettes. 2003. Flow bench applications and techniques, Superflow.

[4] Kalitzin G. and Iaccarino G. 2002. Turbulence Modeling in an Immersed-Boundary RANS-Method, Center for Turbulence Research Annual Research Briefs, Stanford University, California. pp. 415-426.

[5] Franke R. 1982. Scattered data interpolation: Tests of some methods. Math. Comput. 38: 181-200.

[6] Ferziger J. H. and Peric M. 2002. Computational Methods for Fluid Dynamics. Springer-Verlag, third-edition.

[7] Lam C. K. G. and Bremhorst K. A. 1981. Modified Form of Model for Predicting Wall Turbulence. ASME Journal of Fluids Engineering. 103: 456-460.

[8] Wilcox D. C. 1994. Turbulence Modeling for CFD. DCW Industries.

[9] L. Piancastelli, L. Frizziero. 2014. Turbocharging and turbo compounding optimization in automotive racing. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(11): 2192-2199, EBSCO Publishing, USA.

[10] L. Piancastelli, L. Frizziero, G. Donnici. 2014. The common-rail fuel injection technique in turbocharged di-diesel-engines for aircraft applications. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(12): 2493-2499, EBSCO Publishing, USA.

[11] L. Piancastelli, L. Frizziero. 2015. Supercharging systems in small aircraft diesel common rail engines derived from the automotive field. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 20-26, EBSCO Publishing, USA.

[12] L. Piancastelli, L. Frizziero. 2015. Accelerated FEM analysis for critical engine components. Published by Walailak Journal of Science and Technology The Walailak Journal of Science and Technology, Institute

ARPN Journal of Engineering and Applied Sciences

of Research and Development, Walailak University, ISSN: 1686-3933, Thasala, Nakhon Si Thammarat 80161. 12(2): 151-165, Thailand.

[13] L. Piancastelli, L. Frizziero, G. Donnici. 2015. Turbo matching of small aircraft diesel common rail engines derived from the automotive field. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 172-178, EBSCO Publishing, USA.

[14] L. Piancastelli, L. Frizziero. 2015. Multistage turbocharging systems for high altitude flight with common rail diesel engines. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(1): 370-375, EBSCO Publishing, USA.

[15] L. Piancastelli, L. Frizziero. 2015. A new approach for energy recovery and turbo compounding systems for high altitude flight with common rail diesel engines. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(2): 828-834, EBSCO Publishing, USA.

[16] L. Piancastelli, L. Frizziero. 2015. Mapping optimization for common rail diesel conversions from the automotive to the flying applications. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(4): 1539-1547, EBSCO Publishing, USA.

[17] L. Piancastelli, L. Frizziero. 2015. GA based optimization of the preliminary design of an extremely high pressure centrifugal compressor for a small common rail diesel engine. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(4): 1623-1630, EBSCO Publishing, USA.

[18] L. Piancastelli, L. Frizziero, G. Donnici. 2015. Common rail diesel-electric propulsion for small boats and yachts. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(6): 2378-2385, EBSCO Publishing, USA.

[19] L. Frizziero, I. Rocchi. 2013. New finite element analysis approach. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 11(2): 85-100, Allahabad, India.

[20] L. Piancastelli, L. Frizziero, E. Pezzuti. 2014. Kers applications to aerospace diesel propulsion. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(5): 807-818, EBSCO Publishing, USA.

[21] L. Piancastelli, L. Frizziero. 2015. Diesel ecu mapping optimization for aircraft and helicopter applications. JP Journal of Heat and Mass Transfer. ISSN 0973-5763, 11(2): 151-167, Pushpa Publishing House, India.

[22] L. Piancastelli, L. Frizziero. 2015. Fuel consumption reduction and power downsize via robotized multiple speed gearbox and automatic selection system for an automotive application. JP Journal of Heat and Mass Transfer. ISSN 0973-5763, 12(2): 197-210, Pushpa Publishing House, India.

[23] L. Piancastelli, M. Forghieri, L. Frizziero, L. Chinni, M. Cremonini. 2015. Large HSDI CR diesel engines multiple injections and multiple swirls concept. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(18): 7919-7928, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[24] L. Piancastelli L., Frizziero G. Donnici. 2015. Common rail diesel - Automotive to aerial vehicle conversions: An update (Part I). Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(6): 2479-2487, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[25] L. Piancastelli, L. Frizziero, A. Rotondi. 2015. Optimum installation of a common rail diesel engine on a “classical” helicopter: The UH1. JP Journal of Heat and Mass Transfer. 12(1): 45-64, 2015.

[26] L. Piancastelli, L. Frizziero, G. Donnici. 2015. A new concept for low inertia electric turbocompounding in racing spark ignition engines. JP Journal of Heat and Mass Transfer. 12(1): 1-14.

[27] L. Piancastelli, L. Frizziero. 2015. Preliminary optimization of a common rail direct injection diesel alternative to the AE2100 class turboshafts. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(11): 4738-4747, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[28] L. Frizziero, I. Rocchi, G. Donnici, E. Pezzuti. 2015. Aircraft diesel engine turbocompound optimized. JP Journal of Heat and Mass Transfer. 11(2): 133-150.

[29] L. Piancastelli, L. Frizziero, G. Donnici. 2015. The meredith ramjet: An efficient way to recover the heat wasted in piston engine cooling. Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(12): 5327-5333, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[30] L. Piancastelli, L. Frizziero, G. Donnici. 2015. Common rail diesel - automotive to aerial vehicle conversions: An update (Part II). Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(8): 3286-3294, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[31] L. Piancastelli, L. Frizziero, G. Donnici. 2015. Common rail diesel - automotive to aerial vehicle conversions: An update (Part III). Asian Research Publishing Network. ARPN Journal of Engineering and Applied Sciences. ISSN 1819-6608, 10(14): 5823-5830, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[32] Kuechemann D., Weber J. 1958. Aerodynamics of propulsion. Mc Graw Hill, 1958

[33] L. Piancastelli, M. Pellegrini. 2007. The bonus of aircraft piston engines, an update of the Meredith effect. J. Heat and Technology. 25(2).

[34] 2002. Vehicle Engine Cooling Systems: Assessment and Improvement of Wind-Tunnel Based Evaluation Methods, A thesis submitted in accordance with the regulations for the degree of Doctor of Philosophy by Eton Yat-Tuen Ng, Vehicle Aerodynamics Group, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, Australia.

[35] G. Caligiana, S. Pippa. 2005. GradH-Correction: Guaranteed sizing gradation in multi-patch parametric surface meshing. International Journal for Numerical Methods in Engineering, ISSN: 1097-0207. 62(4): 495-515.

[36] A. Ceruti, G. Caligiana, F. Persiani. Comparative evaluation of different optimization methodologies for the design of UAVs having shape obtained by hot wire cutting techniques, 2013, International Journal on Interactive Design and Manufacturing. 7(2): 63-78

Symbols

Symbol	Description	Unit	Value
$V_{aircraft}$	Aircraft cruise velocity	m/s	-
$V_{automotive}$	Car radiator design velocity	m/s	-
$f_{reduction}$	Cooling reduction factor from car to aircraft	-	0.57
f_{climb}	Cooling reduction factor from cruise velocity to climb velocity	-	1.15
m_c	Coolant mass flow	kg/s	-
m_a	air mass flow	kg/s	-
c_{pa},C_p	Air specific heat capacity at constant pressure	J/kg	
T_{ci}	Coolant temperature at radiator inlet	C	89
T_{co}	Coolant temperature at radiator outlet	C	80
T_{ai}	Air temperature at radiator inlet	C	40
T_{ao}	Air temperature at radiator outlet	C	-
Q	Heat rejection rate	kW	-
k_L	Pressure loss factor	Pa^{-1}	
v	Radiator inlet air velocity	m/s	-
μ	Viscosity	Pa s	-
s	Radiator thickness	m	-
s_0	Reference radiator thickness	m	0.027
S	Radiator frontal surface	m^2	
p_{rad}	Radiator fins pitch	m	-
α	Air global heat rejection factor	$kW\ K^{-1}\ m^{-2}$	-
k	Air thermal conductivity	$W\ K^{-1}\ m^{-1}$	-
μ_0	Reference viscosity stratosphere	Pa s	18.27E-6
T_0	Refence viscosity temperature stratosphere	K	291.5

ARPN Journal of Engineering and Applied Sciences

C	Viscosity constant	K	120
V_i	Aircraft velocity @ 20000m	M	-
p_B	Diffuser outlet pressure (station B)	Pa	-
ρ_B	Diffuser outlet air density (station B)	kg/m^3	-
T_B	Temperature (station B)	K	-
V_B	Velocity (station B)	m/s	-
A_3,A_B	Diffuser outlet area=radiator area	m^2	1
Ai	Diffuser inlet area	m^2	0.35
η	Diffuser efficiency	-	-
r	Diffuser compression ratio	-	
thk	Radiator pack thickness	m	-
th_{air}	Air charge radiators thicknesses	m	-
$th_{coolant}$	Coolant radiator thickness	m	-
th_{oil}	Oil radiators thicknesses	m	-
ΔT_{air}	Temperature difference aftercooler	C	-
Q_{air}	Heat rejection aftercooler	kW	-
$T_{air\_coolant}$	Air exit temperature from aftercooler	C	-
$\Delta T_{addbyair}$	Air temperature increase aftercooler	C	-
$p_{coolant}$	Air pressure after the aftercooler	Pa	-
$\rho_{coolant}$	Air density after the aftercooler	kg/m^3	-
$v_{afteraircooler}$ $v_{coolant}$	Air velocity after the aftercooler	m/s	-
$\Delta T_{coolant}$	Temperature difference between cooling air and coolant	C	-
$Q_{coolant}$	Heat rejection required by the coolant radiator	kW	-
H_B ,D_B D_3	Radiator height=diffuser outlet area	m	-
p_3	Radiator outlet pressure (station 3)	Pa	-
P_0	Outside air pressure 20000m	Pa	5475
V_3	Air velocity after radiator (station 3)	m/s	-
ρ_3	Air density after radiator (station 3)	kg/m^3	-
T_3	Air temperature after radiator (station 3)	K	-
$p_{\_loss}$	Total ressure drop of radiator pack over diffuser pressure recovery	%	-