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COOLING SYSTEM OPTIMIZATION FOR LIGHT DIESEL HELICOPTERS

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ABSTRACT

CRDID (Common Rail Diesel Engine) main advantage is the reduced fuel consumption, the safety and the flight readiness. In fact, diesel fuel is available everywhere and flights to airports just for refueling can be avoided. However, diesel engines are generally heavier than turboshaft and require cooling. This necessity is particularly important during near stationary operations of the helicopter. If fans are used for the cooling system, the available power is reduced with an increased penalty weight for the installation. For this reason the ejector exhaust system can be successfully used in CRDID powered helicopters. A feasibility study for the installation of a CRDID (Common Rail Diesel Engine) on a common light helicopter (AB 206) is introduced. The total mass available for the CRDID is evaluated starting from fuel consumption and helicopter data. A derivative of an automotive engine can be used for the turboshaft to CRDID powererplant conversion. The result is that the installation is indeed possible and the payload can be slightly increased in the diesel powered helicopter due to more power available.

Keywords: diesel cooling helicopter ejector exhaust.

INTRODUCTION

Starting from raw data, the turboshaft engine provides has a better power to weight ratio than CRDIDs (Common Rail Diesel Engine). In fact, the improvements in turboshaft engines in the late 20th century have been essential for helicopter development. Turboshaft engines were the premium choice for the helicopter powerplants. However, growing fuel costs with low fuel efficiency of small turbines have reduced the turboshaft advantage. In the automotive world the introduction of CRDIDs have brought into the market several extremely cost-effective power unit with acceptable power to mass ratio. These engines may, in the helicopter conversion, reach an efficiency of 50% without secondary cycles for exhaust energy recovery. CRDID have reintroduced the option of powering light to medium single/twin engine(s) helicopters with advanced piston engines instead of conventional small turboshafts. This solution may contain costs; reduce pollutant emissions and fuel consumption. Soaring oil prices, high operating costs and growing public concern for environment protection have also become essential factor in future choices. This paper provides an answer to the question of what is the optimal diesel engine for a light helicopter, starting from its expected performances. In order to meet this objective, a multi-criteria analysis was undertaken to cover the issues of mechanical and thermal loads and interactions with the helicopter body. A primary advantage of CRDIDs is the possibility to use non-explosive automotive diesel fuel. In fact diesel not only reduces the fire hazards, but also simplifies the supply and storage chain both for civilian and military use. While jet fuel is available mainly in airport, automotive diesel is the most common fuel in the world. A standard private helicopter owner with his own landing site has often to sustain the huge expense of refueling at the nearest local airport. This fact is an important limitation in private helicopter diffusion, especially for light, general aviation helicopters. However, the use of a CRDID with FADEC (Full Authority Electronic Control) poses a significant challenge to the designer, who should reduce fuel consumption, noise levels, emissions, purchase, installation and maintenance costs. Both diesel and Jet fuel can be used in CRDID. This gives huge advantages both on safety and on helicopter usability. In this paper it was also investigated whether conversions from the car-manufacturing industry can be applied to light helicopters. This paper is articulated in the following pars: optimal CRDID choice, CRDID conversion and optimal cooling system design. For this purpose a very common and well known helicopter has been chosen: a version of the Bell 206, produced also by Agusta-Westland with the denomination AB206 (TDCS EASA R140 01_24Oct2014).

The Agusta Westland AB 206 (Figure-1)

Figure-1. An Agusta Bell 206.

The AB 206 data are summarized in Table-1 (from TDCS EASA R140 01_24 October 2014 and EASA TDCS E052 IM RR Model 250 series 2011.06.22).

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Table-1. AB 206 data.

Description	value	unit
TOW	1450	kg
TO power (Transmission)	850	HP
Max Power	405	SHP
Shaft speed	6,000	rpm
Usable fuel capacity	270.7	kg
BSFC (100%)	330	gr/HPh
BSFC (70%)	275	gr/HPh
RR 250-C20 mass	91.2	kg
RR 250-C20 oil capacity	4.5	kg

Preliminary considerations on the CRDID installation

A suitable CRDID for the AB206 has the data summarized in Table-2.

Table-2. Data of a suitable CRDID piston engine for AB206.

Description	value	unit
Engine type	V6	-
Displacement	3,000	cc
Power@TO	450	HP
Mass fully installed	240	kg
BSFC (100%)	158	gr/HPh
BSFC (70%)	128	gr/HPh

The CRDID lower SFC and the excellent off-design performance makes it possible to reduce fuel mass at takeoff. The average fuel consumption of the AB206 is about 91 kg/h. A typical flight with a 30' reserve lasts then 148 min. In fact, in a typical flight with 15 min per hour at 100% and the remaining time at 70% the fuel consumption of the original turboshaft from (1) is 90 kg while for the diesel is 44.16 kg with a fuel mass reduction of r=57.8.

$$Fm = BSFC_{100}\frac{TO_{power}TO_{time}}{60} + BSFC_{70}\frac{Cruise_{power}Cruise_{time}}{60} \quad (1)$$

The available mass for the diesel installation is then (2)

$$Mass_{diesel} = Mass_{turboshaft} + Mass_{fuel}\frac{r}{100} = (91.2 + 4.5) + 270.7\frac{53}{100} = 238[kg] \quad (2)$$

This “available mass” is conservative, since the internal tank can also be reduced in volume and in mass. Another factor to be considered is that the CRDID is not sensitive to high OAT (Outside Air Temperatures) up to ISA+20°C, with a reduction of only 1% for ISA+35°C. The maximum power is usually kept up to 6,000m, depending on the turbocharger choice. The "flat rating" of the turboshaft is not necessary for the CRDID. Equations (1) and (2) demonstrate that, even if the CRDID can be significantly heavier than the original turboshaft, it is extremely convenient to keep the installed CRDID weight as low as possible. In fact, weight is not only linked to performance, but also to fuel consumption (costs) and safety. Two important questions are still to be solved. The torsional decoupling of the system and the cooling of the engine in stationary conditions. While the torsional decoupling of the engine can be obtained through a carbon-carbon clutch with spring damper readily available from the racing-car aftermarket, the cooling is much more critical. In fact, if additional power is required for cooling fans, the available power may be significantly reduced.

The cooling system

The goals for the helicopter cooling system are, in order of priority:

a) Adequately cool the engine in all phases of operation.
b) Maximum reliability.
c) Mass and volume minimization.
d) Power absorption minimization.
e) Cooling drag minimization.

Goal 1. Adequately cool the engine in all phases of flight: ground idle

The engine has to be cooled properly the ground for any length of time. In this phase, overcooling takes place, since the CRDID is so efficient that the energy wasted is not enough to keep the engine warm. This is a problem, since CRDIDs need high temperatures for correct combustion. A thermostatic valve in the liquid cooling system is then strictly necessary.

Goal 1. Adequately cool the engine in all phases of flight: high power takeoff and hovering

High power takeoff and hovering is a very demanding condition, with very high power and no useful airflow. The propeller may induce turbulence that impair the cooling system. Combinations of atmospheric turbulence, high temperature, and irregular ground patterns are known to be critical conditions. The engine should be efficiently cooled at full power, zero airspeed for several minutes; that is possible only with adequate cooling inlets/outlets and an efficient forced airflow. Location of inlets and outlets is critical in helicopters. In the case of the CRDID-AB206, we will use an alternative inlet port for the cooling system and the ejector-exhaust system will have the same position and direction of the turbine outlet.

Goal 1. Adequately cool the engine in all phases of flight: climb

The helicopter may climb at or near full power producing lots of heat. However, in this flying condition there can be some significant airflow going past the aerial vehicle. This airflow makes the cooling job easier because there are high-pressure areas and low-pressure areas somewhere on the fuselage. In climbing, cooling the engine is obtained by taking in cooling air at a high pressure point and exhausts the cooling air at a low pressure point. The ejector-exhaust system will have the same position and direction of the turbine outlet.

Goal 1. Adequately cool the engine in all phases of flight: cruise

This condition is the easiest point to cool the engine. The airflow is nearly steady state; the power settings are from 30% to 75%; the speed is high with plenty of airflow and very well defined pressure areas around the fuselage. In the helicopters, the cruise conditions cannot be optimized at the expense of the first three operating conditions or the helicopter will not hover.

Goal 1. Adequately cool the engine in all phases of flight: descent and landing

Descent and landing conditions are generally characterized by low powered flight at quite good airspeeds until slow down for final approach with higher power settings. The big concern with an CRDID engine is overcooling or shock cooling. A properly set-up of the liquid cooling avoids shock cooling by using a thermostat to re-circulate coolant and avoids over-cooling and shock.

Goal 2. Reliability

The best way to optimize the reliability is simplification of the cooling system. The best solution is to use few moving parts and to select high quality components.

Goal 3. Mass and volume minimization.

The best way to reduce mass and volume is to obtain a sufficient air flow in term of mass rate. F1 racing radiators may be also used for thermal efficiency and reliability.

Goal 4. Power absorption minimization.

In hovering the mass flow rate can be obtained in three ways: by cooling fans, by ejector exhaust and by differential pressure induced by the main rotor. The cooling fan approach requires a relatively large amount of power from the engine, reducing the overall efficiency. The ejector exhaust has the advantage that it is a highly nonlinear phenomenon. At high load and high engine rpm significant differential pressure can be easily obtained. At lower power settings the differential pressure drops more than linearly. Luckily, in helicopters, low loads are associated with cruise, where air is available from airspeed. Therefore, ejector exhausts works pretty well in this application. The differential pressure induced by the main rotor is highly influenced by ground effect, helicopter relative position to the ground and ground morphology. Also the rotation of the helicopter on the vertical (rotor) axis and the direction of the airspeed vector influence differential pressure induced by the rotor. For this reason, this approach is very difficult to implement.

Goal 5. Cooling drag minimization

Reducing cooling drag normally means limiting the airflow and the frontal inlet section of the cooling system. However, cooling can provide additional thrust. This is common for piston aircrafts due to the Meredith effect. Unfortunately, helicopters are penalized in this aspect due to difficulties in the optimization of the Meredith duct. The ejector exhaust solution reduces both the power requirements and the size of inlet and outlet ports.

Cooling system power demand

Cooling demand is a function of power and efficiency. High power and low efficiency increase the amount of heat to be removed from the engine. The traditional pressurized cowls regulate cooling airflow as a function of airspeed and cowl flaps and have no direct link with the cooling rate required by the engine. The ideal cooling system regulates cooling airflow as a function of engine power setting and temperatures. A cooling system incorporating exhaust augmenters is independent of airspeed and fully dependent on power setting, but not on temperatures. Since higher temperatures requires more cooling a thermostatic valve should be included in the liquid circuit. The ejector exhaust allows reduction of cooling drag without compromising engine cooling and requires no additional pilot workload. The absence of fans avoids the subtraction of useful power from the engine.

The engine that needs to be cooled is a V6 automotive engine helicopter conversion. The maximum power required will be 403HP on the takeoff and 280HP in cruise condition. After the cooling air pass through the radiators it flows in the exhaust augmenters; this application needs a single exhaust augmenter, for both banks of cylinders. A single system is used to reduce exhaust size and weight. High temperature CFRC (Carbon Fiber Reinforced Ceramics) can be used to contain the ejector weight.
Ceramic-Resin systems up to 1000°C are currently available.

For the radiator size, Ref [1] uses a classical empirical formula: a radiator that calculates out to 2.48 cubic inch for each HP. This formula holds for radiator radiators of 2.75 inches (69.9mm). The engine used by [1] is a gasoline engine that has an efficiency of about 20%. CRDID have an efficiency of about 50%. Since the fraction of cooling of the radiator is about 1/3 of the total heat dissipation, the CRDID radiator is about half of one of the gasoline engine.

$$V = 405HP \times 2.48 = 1004\ in^3 \qquad (3)$$

With a standard thickness of w=2.75", the "frontal area" A_{tot} of the radiator will be

$$A_{tot} = V/w = 1004/2.75 = 365\ in^2 \qquad (4)$$

As a rule, the cooling duct should not diverge by more 7 degrees to avoid airflow separation. In this way air slows down and builds pressure following the Bernoulli's principle. However, the trumpet shape is to be preferred to the straight one. The best choice is a rectangular inlet duct opening.

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The augmenter is jet compressor that uses a smaller high-speed jet of gas to move a larger volume of cooling air. In this case, the augmenter forces the cooling air through the radiator.

The augmenter has the inlet, the constant and the diffuser sections. The inlet is shaped for smooth entry of the cooling air and positioning of the exhaust jet. In small aircrafts, the optimum inlet area is 15% that of the radiator frontal area [1]. This optimum inlet has a width to depth ratio of 5 [2]. The diffuser can be omitted to save weight and drag. However, the expansion of the exhaust and cooling flow in the diffuser results in a depression increase at the inlet of 40-50% [3] [4] [5].

Preliminary design of the augmenter

A modern CRDID outputs approximately 0.107 pounds per minute of exhaust gas per engine HP at full load. This number is obtained with the following assumptions [6] [7] [8] [9] [10]:

a) CRDID efficiency is 38% (158 gr/HPh).

b) Air to fuel mixture is 17:1 in mass.

The exhaust mass flow of our CRDID will then be:

$$M' = TO_{power} * 0.107 = 43.3[lb\,x\,\text{min}] \quad (5)$$

A normal exhaust temperature for a CRDID is 650°C (923.15K). Therefore, the exhaust density can be approximately evaluated at sea level with (6).

$$\rho_{air923.15K} = \frac{p_{atm}}{RT_{923.15K}} = 0.3824\ [\frac{kg}{m^3}] \quad (6)$$

A good velocity value for the exhaust is $v_{exhaust}$ =400 m/s. The exhaust diameter is then (7).

$$d_{exhaust} = \sqrt{\frac{\dot{m}_{diesel}*4}{\pi * v_{exhaust} * \rho_{air923.15K}}} = 0.052\ [m] \quad (7)$$

The ideal exhaust augmenter has a mass flow ratio of 6:1. That means that the ejector exhaust can move 6 kg of cooling air for every kg of exhaust gas. The diameter of the mixing cross section area is then (8):

$$d_{augmenter} = d_{exhaust}\sqrt{10} = 0.165\ [m] \quad (8)$$

The optimum area ratio between the cross section of the mixing section and the exhaust jet should be 10:1. The length of the mixing section should be 6 or 7 diameters (9).

$$L_{mixing\_section} = d_{augmenter} 6 \approx 1\ [m] \quad (9)$$

The optimum augmenter includes a diffuser section. This section can be added if the cooling is not sufficient. However, due to weight and drag considerations, it can be considered a secondary option in case of problems during tests. The optimum outlet/inlet area ratio of the diffuser is 1.87. The diffuser should not expand with any more than a 14 degree included angle. Up to 15 hPa pressure rise can be obtained in this way between the inlet and the outlet of the augmenter. This cooling system has 3 moving parts, the thermostatic valve, the electric water pump and the pressure relief cap.

Analysis of cooling-duct geometry

An oblique duct with the radiators along the right cylinder rows was initially designed as the lightest and simple solution simple (Figure-2). The CFRP ejector exhaust mixing section is installed on the helicopter tail with the diffuser point rear and upward. A cutaway of the CFD model is depicted in Figure-4. The intercooler and the liquid cooler compose the radiator pack as a porous media. The fresh air enters laterally into the intercoolers, passes into the liquid cooler then is deviated 90° rearwards.

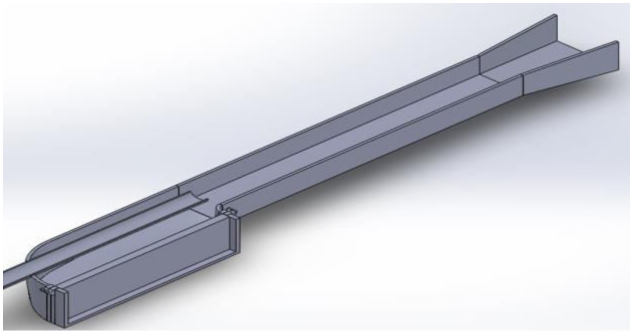

Figure-2. Cooling system duct. First design.

Simulations of the mixing duct were made to visualize the velocity pattern, the cooling efficiency and the pressure differential. The results showed that the input flow rate is not constant along the section of the radiator, but it is greater as it approaches the curve. Therefore, the efficiency of the radiator is farther from optimal (Figure-3). This duct is even less efficient as the ejector exhaust flow is not constant even in the interior cross sections. Turbulence reduces the effectiveness of this cooling arrangement.

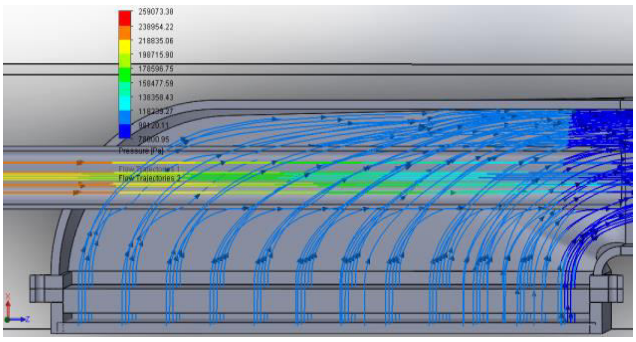

Figure-3. Cooling system duct. Air velocity. First design.

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Conveyors of different geometry and size were then introduced to overcome this problem and to compensate this imbalance by redirecting the flow along the radiator inlet area.

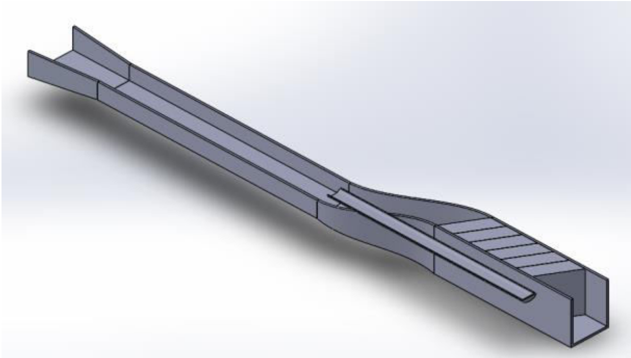

Figure-4. Final solution for the cooling duct.

This solution would have increased the efficiency of the radiator and of the ejector-exhaust. However, despite the use of different types of conveyors, the flow remained uneven along the cross sections and, therefore, these solutions were discarded.

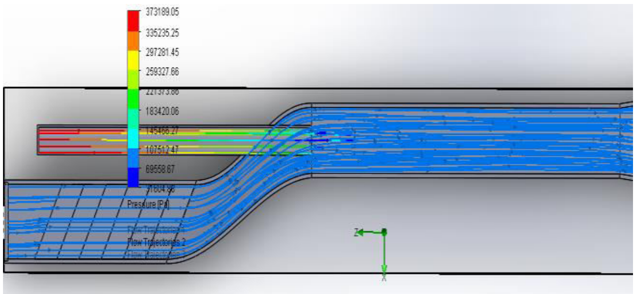

Figure-5. Air flow. Final solution.

CONCLUSIONS

The installation of a conversion of an automotive CRDID proved to be feasible. However, the automotive diesel engine requires expensive surface treatments and part replacements. The automotive conversion would not have an excessive mass and will maintain the payload with the same TOW. In order to reduce fuel consumption and to keep the engine properly cooled, an ejector exhaust cooling system has been designed. The new CRDID assembly can preserve the performances of the original turbine-powered helicopter. The advantage of the CRDID conversion will be nearly halved fuel consumption and the possibility of use of diesel fuel with reduced fire hazards and easy supply. It is also possible to have the equivalent of Euro 6 automotive standard by adding a SCR (Selective Catalytic Reduction) system. The ejector exhaust installation proved to be critical. The best solution is with two ejector exhaust systems, on for each bank of the V6 CRDID. This arrangement is similar to the Ferrari F1 (2006). Two air ducts are positioned on the side of the main gearbox. The radiators are installed in these ducts (Figures 5 and 6).

Figure-6. Ferrari F1 2006. See the lateral air intake.

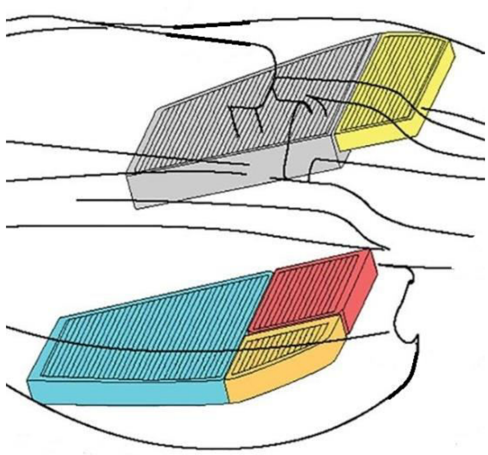

Figure-7. Formula 1 radiators installation.

Symbols

Symbol	Description	Unit
F_m	Fuel mass burned	kg
$BSFC_{100}$	Brake Specific Fuel Consumption at 100% output	gr/HPh
$BSFC_{70}$	Brake Specific Fuel Consumption at 70% output	gr/HPh
TO_{power}	Power required at Take Off (100%)	HP
$Cruise_{power}$	Power required at Cruise (70%)	HP
TO_{time}	Time at full Power (TO_{power})	min
$Cruise_{time}$	Time elapsed at at Cruise Power level (Cruisepower)	min
M_{diesel}	Mass of the diesel engine	kg
$M_{turboshaft}$	Mass of the turboshaft	kg
M_{fuel}	Total mass of usable fuel	kg
r	Fuel Mass needed for the diesel/Fuel mass turboshaft	-
e	TmaxAvio/TmaxAuto	-
V	Radiator volume	inc^3
A_{tot}	Total frontal Area radiator	inc^2
w	Radiator thickness	inc
M'	Exhaust mass flow of CRDID	lb/min
p_{atm}	Atmospheric pressure at ground level ISA+0	Pa
R	Air Gas Constant	J/(kg.K)
$T_{1123.15K}$	Exhaust gas temperature	K
$\rho_{air1123.15K}$	Mass density of exhaust gas at 1123.15K	kg/m^3
$V_{exhhaust}$	Exhaust gas velocity	m/s
$d_{exhaust}$	Exhaust diameter	m
m'_{diesel}	M’ in metric units	m^3/s
$d_{augmenter}$	Augmenter mixing section diameter	m
$L_{augmenter}$	Augmenter mixing section length	m

REFERENCES

[1] C. D. Airesman, Jr., Subaru EJ-22 Installation in a Varieze, Contact. (47): 6.

[2] S. J. Miley. Review of Liquid-Cooled Aircraft Engine Installation Aerodynamics. Contact. (17): 13.

[3] Turbo Tom Wyatt III. Adequate Cooling of Liquid-Cooled Engines. Contact. (40): 13.

[4] Cooling Systems with Exhaust Augmenters by: Daniel R. Nicoson (email: A6intruder [a] adelphia.net).

[5] E. J. Manganiello and Donald Bogatsky: 1945. An Experimental Investigation of Rectangular Exhaust-Gas Ejectors Applicable for Engine Cooling. NACA Report No. 818.

[6] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo. 2012. Fuzzy control system for aircraft diesel engines, International Journal of Heat and Technology, ISSN 0392-8764. 30(1): 131-135.

[7] L. Piancastelli, L. Frizziero and I. Rocchi. 2012. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology. 30(2): 121-126.

[8] L. Piancastelli, L. Frizziero, N.E. Daidzic, I. Rocchi. 20136. Analysis of automotive diesel conversions with KERS for future aerospace applications. International Journal of Heat and Technology, ISSN 0392-8764. 31(1).

[9] 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, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.