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HIGH ALTITUDE OPERATIONS WITH PISTON ENGINES POWER PLANT DESIGN OPTIMIZATION PART V: NOZZLE DESIGN AND RAMJET GENERAL CONSIDERATIONS

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ABSTRACT

In stratospheric flights with piston powered aircrafts, the cooling system takes part to the vehicle design optimization process. An integrated design of the cooling duct(s) is strictly necessary. At high altitudes, the cooling air is taken from high-pressure areas into a subsonic ramjet: the Meredith cooling duct. A diffuser reduces the airspeed and increases the pressure of the cooling air. Then a group of high performance finned radiators rejects the heat from coolant, air charge and lubricant. A variable geometry nozzle transforms the added enthalpy into speed and thrust. The nozzle is positioned in a low pressure, high turbulence area. The nozzle design and the duct thrust are discussed in this paper. At first the results from Parts I to IV are summarized and discussed. The resulting data are also exposed and summarized. The pressure recovery and heat rejection are evaluated in function of aircraft speed for a 1-m^{2}vertical-radiator circular duct. The nozzle is then optimized and the total thrust is evaluated.

Keywords: optimization, HALE, UAV, nozzle, ramjet, meredith effect.

1. INTRODUCTION

Propulsion system ofUAVs(Unmanned Aerial Vehicle) 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 after coolers 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 TCsize.

Automotive derived spark ignition and diesel piston engines are available up to 700HP. In these engines the intake is pressurized with three cascaded stages of automotive derived TCs up to about 200HP. Over this power level the engine requires an axial supercharging system that can be derived from commercial turbines as it has been done on the STRATO 2C. It is also possible to have an emergency additional power system as described in the VD007 hybrid arrangement [1] [2] [3] [4] [5] [6]. Due to lower air mass requirement and flat rating piston engine are a more efficient choice for stratospheric aircrafts than turboshafts and turbojets. However, modern piston engine propulsion systems lack of the huge technical background of turbines. In fact, after WWII the research in this field have been discontinued, while turbines have experienced enormous development that led to extremely reliable and efficient designs. The proof is given by the fact that the record flight altitude of Mario Pezzi with his Caproni of 1939 has been overcome only in 1995 by Grob-Strato2C. Curiously, as it happens in many cases, the Formula 1, Reno Racing and WWII experience in cooling systems have been mostly neglected by the designers of new remarkable piston-powered research stratospheric aircrafts. Also the development costs were underestimated. In fact, the knowledge gap left in these 50 years of "turbines only" cannot be filled without proper trials and errors. The solar-powered alternative cannot fill this gap due to the low wing loading needed by this application. The stratospheric aircraft needs to pass the troposphere atmosphere with its environmental problems to reach stratospheric altitudes. Low wing loading reduces aircraft control and overloads structures.

As it was introduced in previous paper the most critical part of the cooling duct is the identification of a high pressure area for the intake and a low pressure one for the nozzle. Straight, all external ducts are theoretically possible, but the external drag prevents high thrusts for this solution. In fact, radiator powered, subsonic ramjets suffer from the lack of high temperatures. As it was shown in part IV of this paper, the use of the highest oil temperatures of 150 DEG C outputs air at about 135 DEG C that is the maximum achievable practical temperature for heated air in the Meredith duct. Theoretically, it is possible to recover energy also from turbo charging turbine housings, but the high temperatures would require highly pressurized systems or specialized coolants with all the annexed weight, reliability and safety problems. Two alternative solutions have been devised for Meredith's ram ducts. The first one is to embed long slim radiators into the wings as in the De Havilland Mosquito and the Messerschmitt Bf 109 F-K. This solution makes it possible to reduce divergent length, which goes with radiator height. However, it faces high pressure loss due to the unfavourable internal surface to perimeter radio (hydraulic diameter).

Another solution is to embed the duct inside the fuselage or the nacelle, leaving only the intake exposed to the incoming air. This most favourable solution takes the air from the last 1/3 or the wing and positions the exhaust on the upper part of the fuselage or the nacelle. This solution is a hybrid from the P51 Mustang and the Formula 1 cooling duct and obtains the best compromise for optimum performance. An inclined, thin radiator

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package composed by intercooler(s), after cooler, liquid coolant and oil coolant offers the maximum temperature rise for the cooling air slowed down by the diffuser. The diffuser will have an extremely long streamline shape. The area ratio from the inlet and the exit of the diffuser is A_i/A_B=0.35 for best efficiency. Formula 1 radiator with 25 FPI (Fin per Inch) can be used to obtain optimum heat rejection with minimum pressure loss (drag). As it has been demonstrated in Part IV, Reynolds and Prandtl number after the diffuser are roughly the same for Formula 1 in stratospheric aircrafts cruising in the range of 0.4-0.7 Mach. A variable geometry nozzle completes the subsonic ramjet cooling duct. Unsurprisingly, many high altitude piston engine applications failed to poor design of the cooling installation. Powerplants and their cooling system have always been a problem up to this day. 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 racing 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 0.7 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 general-aviation 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.

Subsonic ramjet heritage

Two short documents are the milestones of ram-jetor athodyd (Aero THermODYnamic Duct) propulsion. The first was published as early as 1913 in the magazine "L'Aerophile" and dealt with a suggestion made by Rene Lorin for a hypothetical flying vehicle described as a "propulseur par reaction directe" (direct reaction propulsion system). Lorin stated that a heated aero duct consisting of an inlet diffuser able to ram incoming air and an attached combustion chamber with suitably shaped expansion nozzle, would produce thrust.

In 1915, Albert Fonó devised a cannon-launched projectile with a ramjet propulsion unit for a long range heavy shell. Fonó patented his invention in May 1928 with German Patent No. 554,906. In Soviet Union, Britain, Germany and United States experiments and theoretical research on supersonic and subsonic ramjets have been carried out during WWII. At the end of the war the subsonic ramjet experience ended due to the much more efficient supersonic solution. However, several experiments of subsonic ramjets from 0.2 up to 0.8 Mach were carried out by the above Nations. These experiments and post-war refinements are the basis of this paper. This research was guided by the following considerations. The ram-jet engine has simple construction and peculiar thrust characteristic, which, similar to drag, rises nearly proportionally to the dynamic pressure and to the main cross-sectional area. Above a given minimum flight speed it is possible to obtain thrust still in the subsonic range. As opposed to rockets and turbo-jets, the ram-jet engine construction is inexpensive and it is suitable for mass production due to the uncomplicated shape of the engine and the absence of moving parts. The engine is largely insensitive to the kind of fuel or heat source used. German experience is well described in paper [7]. The ramjet was installed on a Dornier Do 17 (Figure-1).

Figure-1. Do 17Z with D3=0.5m ramjet-0.3 M-2,000m (1942) [7].

Figure shows a well dimensioned ramjet with a very high ratio diffuser. The ramjet had a 10-DEG conical diffuser with Ai/AB=0.158 and a nozzle with AB/A4=0.236. The maximum combustion chamber temperature was 600 DEG C. Several different ramjets were developed with D3 increased up to 2 m (Figure-2).

Figure-2. This Do 17Z with a 1.5m ramjet encountered serious stability and handling problems (1943) [7].

For measuring purposes, a duct with D3=1m was selected for final tests. The length of the cylindrical combustion chamber was again chosen of 4000 mm. It had a very high ratio 10-DEG conical diffuser with A_i/A_B=0.158 and a slightly curved intake. The nozzle had A_B/A_4=0.565 and a cone-angle of 11.75 DEG. Tests were carried out at 0.3-0.37M and altitudes from 1000 to 7000m.

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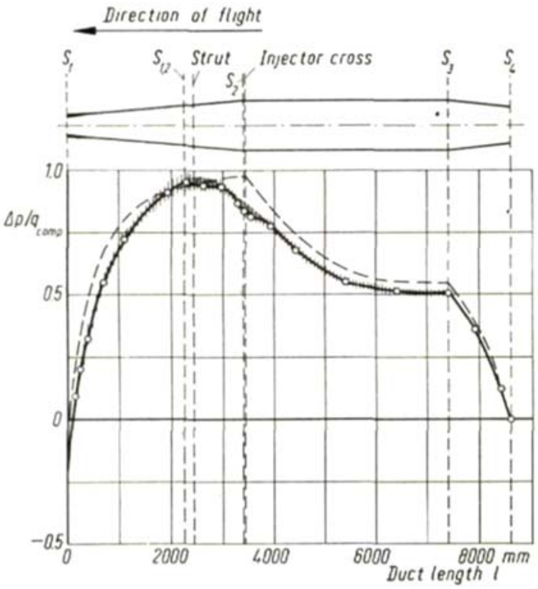

Figure-3. Pressure on aD3=1m ramjet at 4000m, V_0=0.3M (continuous line) vs. theoretical ones (dotted line) (1943) [7].

Curiously, the calculations were made with unitary diffuser efficiency and 0.95 nozzle efficiency. This approach is common to RAE theoretical estimations. Figure 3 shows that the estimation for the nozzle is fully acceptable, while the theoretical diffuser performance was overestimated. In radiator heated ducts the diffuser estimation is extremely important due to the limited air enthalpy increase. The nozzle performance is almost isentropic for the Meredith's ramjet due to reduced velocity and friction.

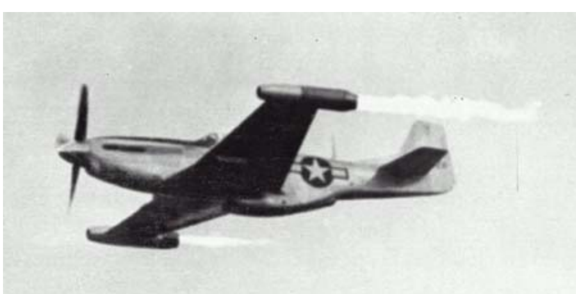

Figure-4. Ramjet powered P51 Mustang (1945).

The poor results on a few aircrafts with ramjets (see Figure-4) ended the experiments on subsonic ramjets.

Nozzle

In the dimensioning of the nozzle, it is possible to neglect both the distributed and the concentrated losses. So, the only problem is to evaluate the influence that the presence of the nozzle has on the pressure drop of the radiator.

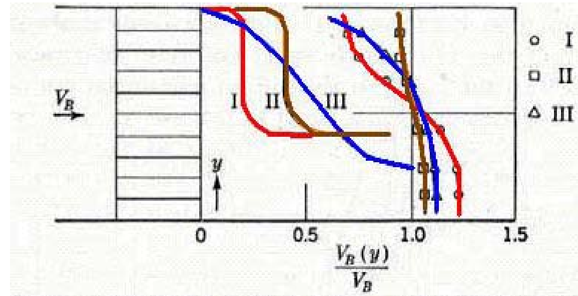

Figure-5. Velocity pattern at the radiator back face in function of parameter a (see Figure-6).

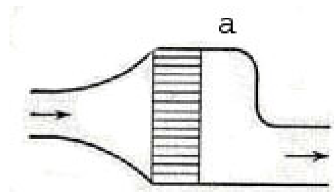

Figure-6. Volume on the radiator back (parameter a).

Figure-5 shows the brown profile assures an almost constant distribution of the air velocity in the radiator back. The most important parameter in dimensioning the nozzle is the distance *a* between the nozzle throat and the radiator (Figure-6). An increase the of ratio between *a* and the radiator height H_B reduces the radiator drag due to the more uniform velocity on the radiator back (Figure-7).

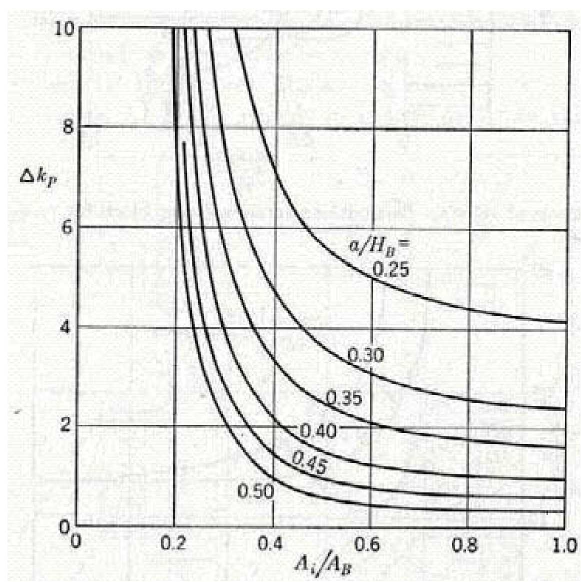

Figure-7. Radiator drag coefficient k_p as a function of a/H_B and diffuser area ratio A_i/A_B (<1).

Finally, the duct can be equipped with a variable nozzle. Figures 8 and 9 shows the flap system mounted on the Bf 109.

Figure-8. Messerschmitt Bf 109 Friedrich? with the nozzle fully opened.

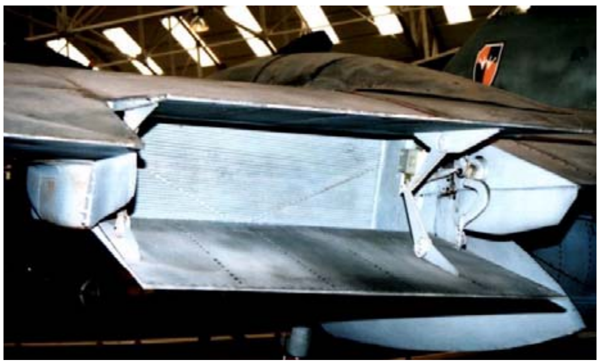

Figure-9. Bf109 with the nozzle fully opened (possibly a late G or K due to the absence of the boundary layer bypass duct).

Cooling duct regulation through variable intake flap proved to be not efficient (Figure-6).

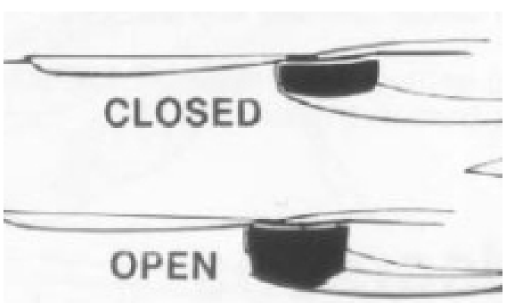

Figure-10. Variable air intake on early P51 Mustang prototypes proved to be ineffective.

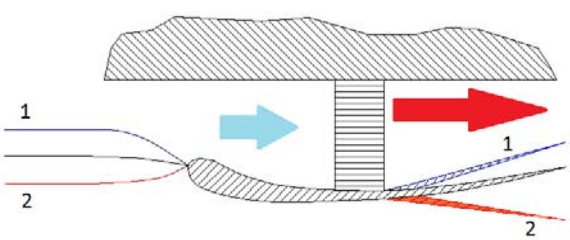

Figure-11. Nozzle influence on duct air flow.

Figure-10 shows that the ability of the subsonic duct to suck air increases by opening the nozzle from position 1 to 2. This effect takes place with extremely high efficiency only if the intake area is smaller than the nozzle throat area.

Nozzle design

The first value to be evaluated is the parameter a of figure 2. In the example of parts I-IV of this paper the cooling duct is circular with a diameter (vertical radiator section) of D_B=1.128 m (A_B=1m^2). The diffuser ratio is A_i/A_B=0.35.From Figure-3 a/HB is then 0.5.

$$a = 0.5 \times 1.128 = 0.564\,[\mathrm{m}] \tag{1}$$

An additional volume of 0.564 m^3(the radiator section of the duct is of unitary area) should then be added after the radiator before the subsonic convergent nozzle. The air is heated by the radiator (thickness=27mm). For the airspeed of Mach 0.4 and the coolant temperature of 150 DEG C has the following parameters: T_3=498 K, p_3=5725Pa, ro_3=0.04kg/m3, V_3=88m/s. The speed of sound at station 3 is (2):

$$M_3 = \sqrt{k \cdot R \cdot T_3} = 447 \tag{2}$$

and

$$Ma_3 = \frac{V_3}{M_3} = 0.196 \tag{3}$$

The total parameters at station 3 are then (4) (5) and (6):

$$T_{03} = T_3 \cdot \left(1 + \frac{k-1}{2} \cdot Ma_3^2\right) = 411.2[K] \tag{4}$$

$$p_{03} = p_3 \cdot \left(1 + \frac{k-1}{2} \cdot Ma_3^2\right)^{\frac{k}{k-1}} = 5882[Pa] \tag{5}$$

$$\rho_{03} = \rho_3 \cdot \left(1 + \frac{k-1}{2} \cdot Ma_3^2\right)^{\frac{1}{k-1}} = 0.041\left[\frac{kg}{m^3}\right] \tag{6}$$

The Meredith duct thrust is maximized when the nozzle throat area is the minimum possible. For nozzle efficiency the condition $A_4 > A_i$ (nozzle throat area larger than intake area) should hold.

It is then possible to assume that $A_{4c}=1.05A_i$, being a mere 5% increase the minimum technically significant. If a tentative value of Ma_4 is assumed, it is possible to iterate to the correct value that satisfy the chosen A_{4c}. Equation (7) expresses the energy conservation principle.

$$p_{03} = p_{04} = p_4\left(1 + \frac{k-1}{2} \cdot Ma_4^2\right)^{\frac{k}{k-1}} \tag{7}$$

It is then possible to evaluate V_4 from the equation of isentropic transformation (8).

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$$V_4 = \sqrt{\frac{2k}{k-1}} \cdot \sqrt{\frac{p_{03}}{\rho_{03}}} \cdot \sqrt{1 - \left(\frac{p_4}{p_{03}}\right)^{\frac{k-1}{k}}} \quad (8)$$

The ideal gas principle outputs T_4 (9) and ρ_4 (10).

$$\sqrt{k \cdot R \cdot T_4} = \frac{V_4}{Ma_4} \quad (9)$$

$$\rho_4 = \frac{p_4}{R \cdot T_4} \quad (10)$$

Equation (11) expresses the mass conservation principle.

$$V_3 \rho_3 A_3 = Q_4 \rho_4 = 3.5 \left[{kg}/{s} \right] \quad (12)$$

It is then possible to obtain A_4 (13).

$$A_4 = \frac{Q_4}{V_4} \quad (13)$$

Ma_4 is modified until the desired value for A4 is obtained. In this case the optimum value for the exit velocity Ma_4, that matches $A_{4c}=1.05A_i$, is0.58 Mach.
It is then possible to evaluate the thrust (14).

However, at this speed p_4 is lower than p_0 (outside air pressure). Therefore, if $p_3=p_4$ we have $Ma_4=0.32$, $V_4=142$ and $A_4=0.63$.

$$T = V_3 \rho_3 A_3 (V_4 - V_0) = 70[N] \quad (14)$$

The thrust coefficient C_T is expressed by equation (15).

$$C_T = \frac{2T}{\rho_0 V_0^2 A_3} = 0.22 \quad (15)$$

The thrust is then minimal and only an extremely accurate integration of the duct inside the fuselage will avoid having drag instead of thrust from the cooling duct.

This is due to the extremely reduced air mass flow (3.5 kg/s), and the low vehicle speed (0.4 Mach). In common automotive application the maximum oil temperature is kept at 110 DEG C. In this case the thrust is even lower. The speed and the maximum pressure are increased to reach higher values of thrust. At Mach 0.7 it is possible to reach 400 N.

If the radiator thickness and the heat rejection is doubled the thrust at an airspeed of 0.4 Mach is increased up to 121 N (72% increase). The advantage is kept also at Mach 0.7 with a trust of 500N (25% increase). The radiator thickness it then a critical parameter in the duct. An optimum radiator thickness can be found for every diffuser-pressure-recovery and airspeed.

CONCLUSIONS

In stratospheric flights with piston powered aircrafts, it is easy to face cooling problems. At low speeds, below Mach 0.5, it is difficult to obtain a significant amount of thrust even using the Meredith ramjet cooling duct. On the contrary it is extremely easy to face overheating and additional drag from the cooling duct. An optimized design of the cooling duct(s) is then strictly necessary to avoid overheating and to obtain thrust. The cooling air is taken from high-pressure areas into subsonic ramjet: the Meredith cooling duct. 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. A variable geometry nozzle transforms the added enthalpy into speed and thrust. The nozzle is positioned in a low pressure, high turbulence area. The nozzle design and the duct performance have been discussed in this paper. The pressure recovery and heat rejection are shown in function of aircraft speed and coolant temperature for a vertical 1-m^2-radiator circular duct. The nozzle has been then optimized and the total thrust has been evaluated. Afterwards the radiator duct performance as a high altitude ramjet was evaluated. It is extremely important to optimize the radiator thickness and to obtain the maximum coolant temperature possible.

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Symbols

Symbol	Description	Unit	Value
p_i, p_1 p_0	Diffuser Inlet pressure (station 1 = station 0)	Pa	-
ρ_i, ρ_1 ρ_0	Diffuser inlet air density (station 1)	kg/m^3	-
T_i, T_1 T_0	Air temperature inlet (station 1)	K	-
V_i, V_1 V_0	Velocity (station 1)	m/s	-
D_1, D_i D_0	Diffuser inlet diameter (station 1)	m	-
A_1, A_i A_i	Diffuser inlet area (station 1)	m^2	-
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
H_B, D_B D_3	Radiator height=diffuser outlet area	m	-
p_3	Radiator outlet pressure (station 3)	Pa	-
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_{03}	Total pressure (station 3)	Pa	-
T_{03}	Total temperature (station 3)	K	-
ρ_{03}	Total air density (station 3)	kg/m^3	-
M_3	Sound velocity (station 3)	m/s	
Ma_3	Velocity (station 3)	M	
D_4	Nozzle outlet diameter (station 4)	m	-
A_4	Nozzle outlet area (station 4)	m^2	-
ρ_4	Nozzle outlet air density (station 4)	kg/m^3	-

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