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Optimization of a ducted-fan propulsion unit equipped with an internal combustion engine

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The idea of using a heat source for increasing the propulsion efficiency an airplane equipped with piston combustion engine first appeared just before the Second World War. F.W. Meredith [1] describes the mechanism of a radiator placed in a duct inside an airplane’s structure and expresses the basic relations on the aerodynamic resistance of such a structure.

The issue was further processed by H. Winter [3]. In his article: Contribution to the theory of the heated duct radiator, the author derived simple equations allowing to quantify the drag reduction of a radiator due to additional heat with enough accuracy for practical application. Such a relationship is an expression of the law of conservation of energy, where the heat transferred from radiator to ambient air corresponds to engine power - from this relationship, the flow rate in the channels can be easily estimated. The equation is expressed as follows

$$\rho_0 v_1 F g\left[\left(i_2 + A\frac{v_2^2}{2g}\right) - \left(i_1 + A\frac{v_1^2}{2g}\right)\right] = Q,$$

where $i = \frac{\kappa}{\kappa - 1} A \frac{p}{g\rho}$ and $A = \frac{1}{427}$kcal/mkg. The amount of heat can be taken as a fraction of the engine power $Q = A \propto 75N$ (for water cooled engines $\propto \approx$ 0,5), i is internal energy and N is engine power [hp]. Indices 1 and 2 correspond to sections in front of, behind the radiator respectively, 0 at the entrance to the channel.

In a practical sense, the most famous aircraft using the heat from the radiator for thrust is probably the P-51 Mustang. However, the relevant publication was not available at the time of writing this post.

However, the Me-109E concept described in [2] is also interesting. Small radiators are at Me. 109E and I. 110 are located in each wing. Attached is a sketch of this structure near the trailing edge of the wing (Fig. 1). It includes a mechanism for controlling the outlet flap from the channel, with which it is possible to regulate the flow of the cooler with an increase in local losses in the nozzle ("throttling"), which is important in reducing aerodynamic resistance at higher speeds. The author also caused large potential losses caused by the boundary layer, which in this case is significantly developed, since the entrance is on the underside of the wing.

The cited articles are important in determining the methodology of this study and thesis. To quantify the contribution of residual heat to the reduction of aircraft drag, it is first necessary to describe the task analytically. The system of the following equations will serve the purpose:

1. The energy difference in front of and behind the radiator is equal to the delivered heat Q [W], which can be expressed as a fraction of the engine power

$$\dot{m}\left[\frac{p_1}{\rho_0} - \frac{p_2}{\rho_2} + \frac{1}{2}\left({v_1}^2 - {v_2}^2\right)\right] = Q\,.$$

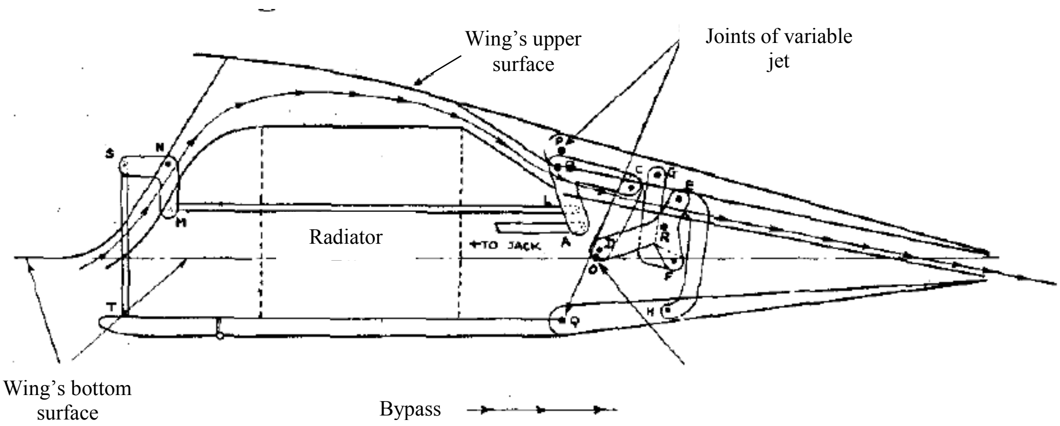

Fig. 1. Radiator duct of Me-109E

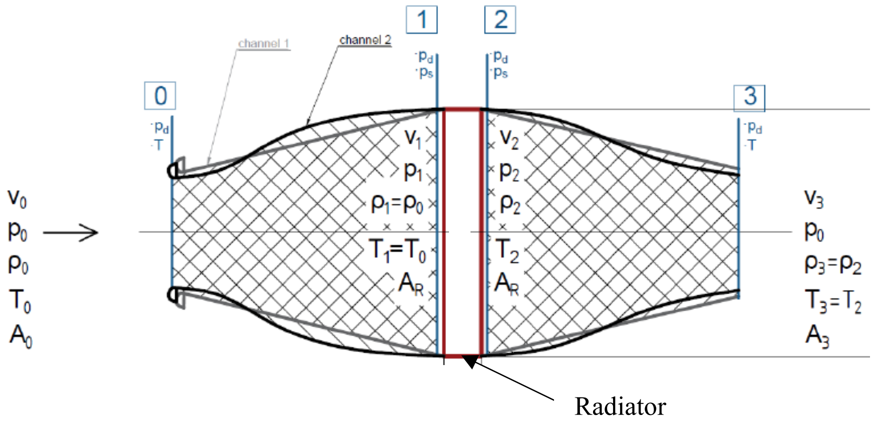

Fig. 2. Reference sections of radiator duct

2. The second important parameter is the pressure loss of the radiator Δp_c. Neglecting the supplied heat (we are talking about a so-called cold radiator), the pressure difference can be expressed by multiplying of the loss coefficient c_w and the dynamic pressure at the inlet to the radiator

$$\Delta p_c = p_1 - p_2 = \frac{\rho_0 v_1{}^2}{2} c_w \,.$$

3. When including the effect of supplied heat, this equation does not apply, because the change in dynamic pressure also plays a significant role here. The pressure loss of the "hot radiator" Δp_h is expressed as the difference of the dynamic pressures in front of and behind the radiator in the sum with $h \cdot c_w = c_{w_h}$ which is the loss coefficient of the hot radiator

$$\Delta p_h = p_1 - p_2 = \rho_2 v_2{}^2 - \rho_0 v_1{}^2 + h \cdot c_w \,.$$

The value of the coefficient h defines the dependence of the pressure loss of the cold and hot radiator. As part of the experiment, the goal is to obtain the value of this coefficient as a function of another known parameter (the literature refers *to* $\frac{1}{2}(\rho_2 v_2{}^2 - \rho_0 v_1{}^2)$, however this is not validated).

4. Remaining equations represent the application of the law of conservation of momentum and the equation of continuity between individual sections of the channel.

$$p_1 - p_0 = \eta_{Di} \frac{\rho_0}{2} ({v_1}^2 - {v_0}^2)\,, \qquad \eta_{Di} - \text{ diffuser efficiency}\,,$$
$$p_2 = p_0 + \frac{1}{2} \rho_2 {v_2}^2 (\beta^2 - 1)\,, \qquad \beta - \text{ section ratio } \mathrm{A_R}/\,\mathrm{A_0}\,,$$
$$\rho_0 v_1 = \rho_2 v_2\,.$$

The output of the system of these equations is $v_2 = f\,(\rho_0;\ p_0;\ v_0;\ Q;\ c_w;\ \beta;\ \eta_{Di})$. Result can be expressed as decrease in the internal drag of a heated radiator in comparison with the unheated condition as the Function of duct opening ratio *A3/AR* (Fig. 3).

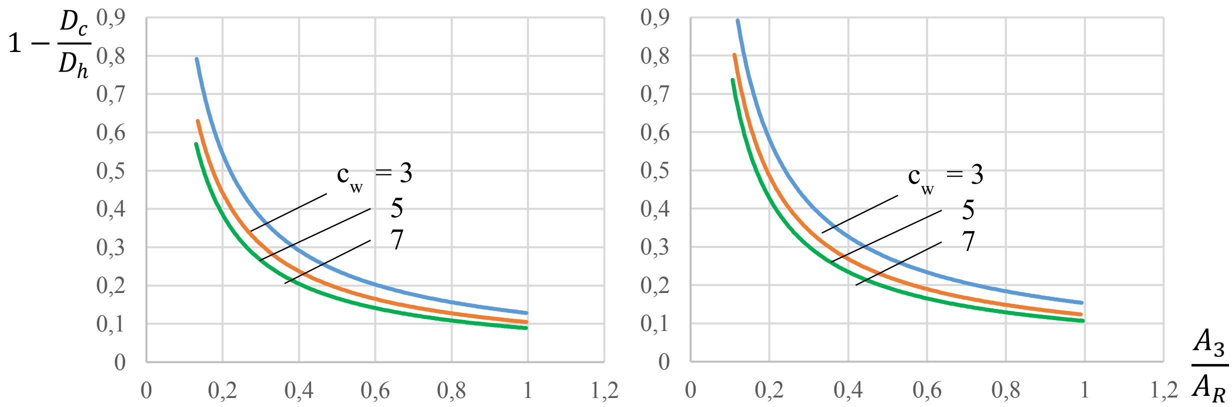

Fig. 3. Decrease in the internal drag of a heated radiator in comparison with the unheated condition as the function of duct opening ratio *A3/AR*

The results of this study were used for designing the flow path of the propulsion unit of the UL-39[1]aircraft developed under the auspices of the Faculty of Mechanical Engineering of the Czech Technical University. Main goal was to optimize the existing structure in order to maximize the efficiency of the drive unit. Inlet part of the unit will be described. The goal was to create an inlet channel with the lowest possible losses and the most uniform flow field on the outlet cross-section (blower inlet).

First, a simulation of the entire aircraft was carried out with the old variant of the drive. The boundary conditions at the inlet were taken from it for further calculations. Furthermore, a multi-criteria optimization was carried out using the adjoint in Fluent, with the help of which a significant improvement was achieved in terms of pressure losses in the channels.

Fig. 4. UL-39 Albi

The UL-39 Albi is a Czech project of a world-unique ultralight two-seater aircraft, built according to the model of the L-39 Albatros jet training aircraft. It is the only ultralight in which the engine does not drive the propeller, but the blower. The development version of the aircraft took off for the first time on April 4, 2016 at the airport in České Budějovice.

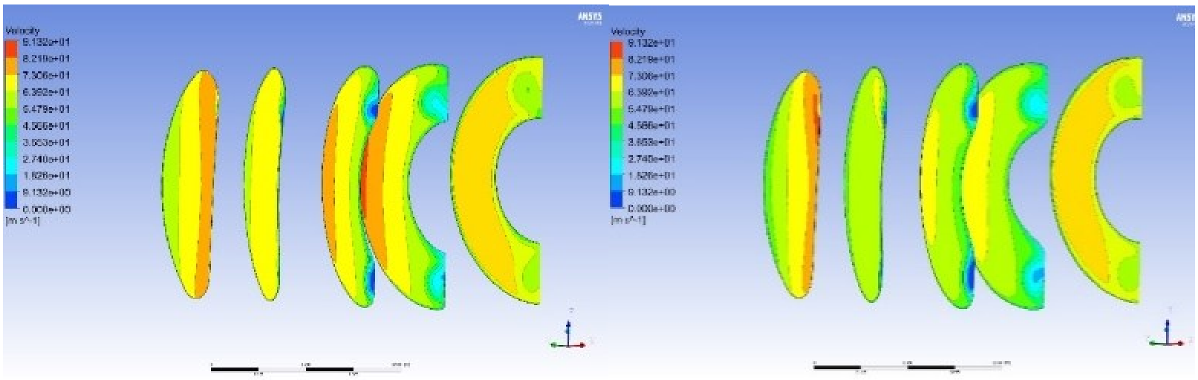

Fig. 5. CFD Analysis of inlet channel of UL-39 Albi

Table 1. Results of CFD analysis of inlet channel - total pressure loss refering to improvement

Velocity [m/s]	Standard deviation of axial velocity	Uniformity index of axial velocity	Total pressure loss	Averange magnitude of tangential velocity
75	4,48%	0,68%	**11,81%**	-1,17%
70	5,46%	0,76%	**15,39%**	-0,67%
55	7,58%	0,91%	**23,96%**	3,92%
40	7,91%	0,95%	**30,78%**	5,82%
25	2,55%	-1,26%	**12,90%**	2,15%

Acknowledgements

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