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STATIC TESTS OF UNCONVENTIONAL PROPULSION UNITS FOR ULTRALIGHT AIRPLANES

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Abstract. This paper presents static tests of a new unconventional propulsion unit for small aviation airplanes. Our laboratory stand – a fan drive demonstrator – enables us to compare various design options. We performed experiments to verify the propulsion functionality and a measurement procedure to determine the available thrust of the propulsion unit and its dependence on engine speed. The results used for subsequent optimization include the operating parameters of the propulsion unit, and the temperature and velocity fields in parts of the air duct.

Keywords: propulsion unit, laboratory stand fan drive, static thrust, available thrust.

1. Description of the propulsion unit

The propulsion unit is a type of structure on the border between a propeller unit and a jet propulsion unit. This unconventional drive unit consists of a low-pressure axial fan stored in the internal channel and driven by an internal combustion engine with composite or dural transmission shafts [1].

The core of the stand contains the first power unit to be chosen — a four-stroke inline four-cylinder engine from the Yamaha R1 model 2004 sports bike. The stroke volume is 998 cm^3 and the power on the crank shaft is 131.4 kW (179 PS) at 12500 revolutions per minute (RPM). The performance of the motor transmits the primary stage of the engine by a constant gear ratio from the crankshaft to the drive shaft, which is attached at the other end to the rotor stage.

The air duct consists of inlet channels, a single-stage low-pressure axial fan with a stator stage, in this case located in front of the rotor stage, and the outlet channel with a nozzle. Fig. 2 shows a schematic drawing of the propulsion system, showing all the main parts and the configuration.

Two inlet channels serve to supply air to the fan. They are located on the sides of the fuselage and they are connected in close proximity to the stator stage. The air is first applied to the stator blades to create a suitable outlet flow, and then it enters the rotor blades driven by a piston engine. The complete geometry is theoretically designed so that there is only an output flow axial velocity component.

The outlet channel is located behind the rotor and is longitudinally divided into two branches. A portion of the air flows directly through the main part of the outlet channel to the nozzle located at the end of the drive, and another portion of the air is streamed through the bottom bypass through the radiator of the engine. A coolant bypass is designed to minimize the pressure loss resulting from the aerodynamic drag of the cooler. The two branches of the outlet channel are then reconnected before the output nozzle. A propulsion airplane is thus produced with a fan in the air duct, or a cold jet.

Figure 1. Engine on the stand.

2. Demonstrator of a propulsion unit

A necessary and logical step in developing the new aircraft concept was to build a testing stand for the engine. The stand for static measurements (at zero forward speed) in laboratory conditions is designed to determine the static thrust characteristics experi-

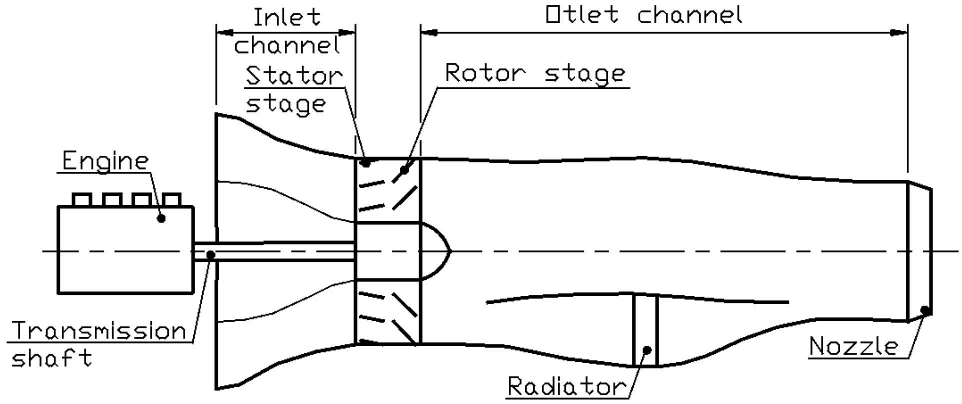

Figure 2. Scheme of the propulsion unit [2].

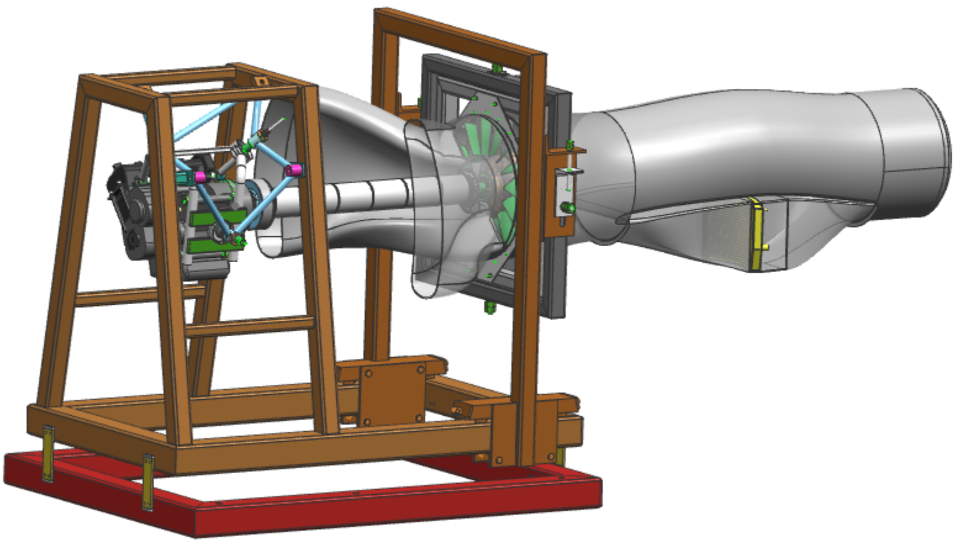

Figure 3. Model of the laboratory stand [1].

mentally for various configurations of the propulsion unit, and also to check the proper functionality of the system. The demonstrator consists of a frame, the engine and the propulsion unit.

Various combinations of propulsion were tested in order to find the appropriate operating conditions. A configuration with two radiators and with one radiator located in the channel, and also the position of the leading edge dividing the air flow in the outlet channel in two ways, and various different nozzles were selected.

3. Components of the laboratory stand

The test stand has dynamometers (HBM U2B/10 kN and U2AD1/500 kg) and strain gauge force sensors installed in the air duct axis to measure the comparative characteristics of various configurations of the driving set-up. Engine speed and the transmission shafts are measured using electrical impulses directly from the control unit. Comparisons were made using a non-contact optical sensor. In the back of the outlet channel, there is a device for attaching and moving six pitot-static probes in the flow field (Fig. 4). This sample is intended to measure the velocity and pressure fields of circular shape. The set-up includes connecting the probes with pressure tubing with pressure transmitters and a DCP DP1 sensor. Several local delivery points of a total and static pressure stream are located in the main channel, in front of, behind, or between the radiators.

The amount of energy transmitted to the engine by the radiator is recorded by the flow indicators of the coolant and by the fluids from the oil-water heat exchanger, together with their input and output temperatures.

The stand includes the deployment of additional thermocouples in the place of the exhaust gas bearing rotor and in the place behind the radiator, using a set of two adjustable and removable temperature control rods.

Fuel consumption when running the engine is measured by weight loss of gasoline, when the density is known. Data management and acquisition was performed with the National Instruments CompactRIO platform.

The device was programmed using measurement ap-

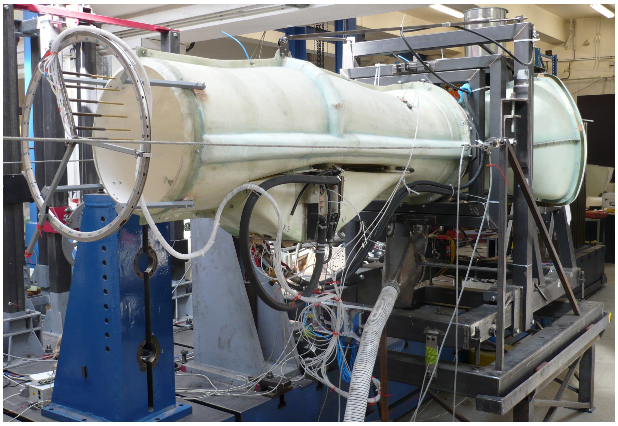

Figure 4. Rear view of the test equipment for measuring performance characteristics [1].

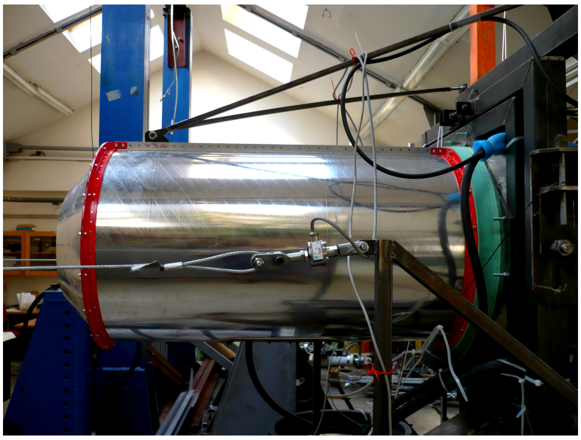

Figure 5. The straight outlet channel.

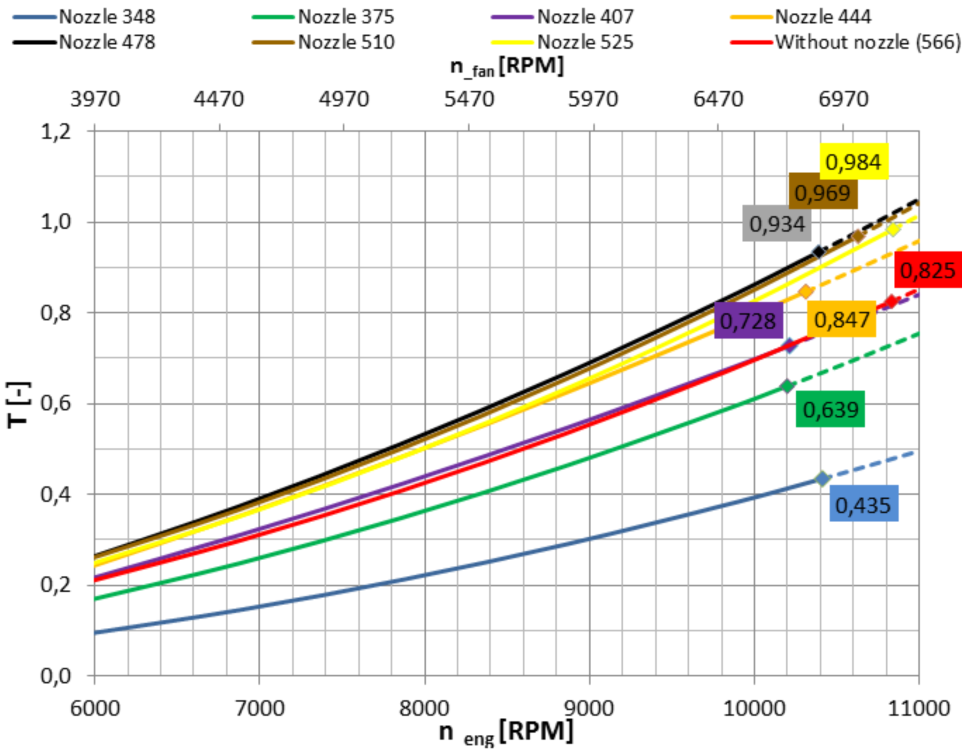

Figure 6. Dimensionless thrust, depending on engine speed/speed fan (the nozzle number corresponds to its diameter).

plications created in LabView graphical programming language.

For the actual measurements of the demonstrator, we used measuring cards — modules NI 9403, 9213, 9237 (2×), 9215 and 9401.

4. Measurement results

To verify and compare the suitability of each drive configuration (one/two radiators, use of a nozzle, and the angle of the leading edge dividing the flow in the outlet channel), measurements were taken of the ventilator unit with the designed shape channel and straight measurements of the outlet channel were made

4.1. Comparing the data with ISA

The thrust values listed below were related to the International Standard Atmosphere (ISA), because the measurements were taken in various climatic conditions (in different seasons). It can be said that the thrust is generally a function of engine speed, atmospheric density, which is specified by relative pressure and temperature, and also the mass flow of the fuel and the flight Mach number [3, 4].

In our propulsion type and under our measurement conditions, the dependence can be simplified to:

$$\frac{T}{\delta} = f\left(\frac{n}{\theta^{1/2}}\right), \quad \text{where } \delta = \frac{p}{p_0},\ \theta = \frac{T}{T_0}.$$

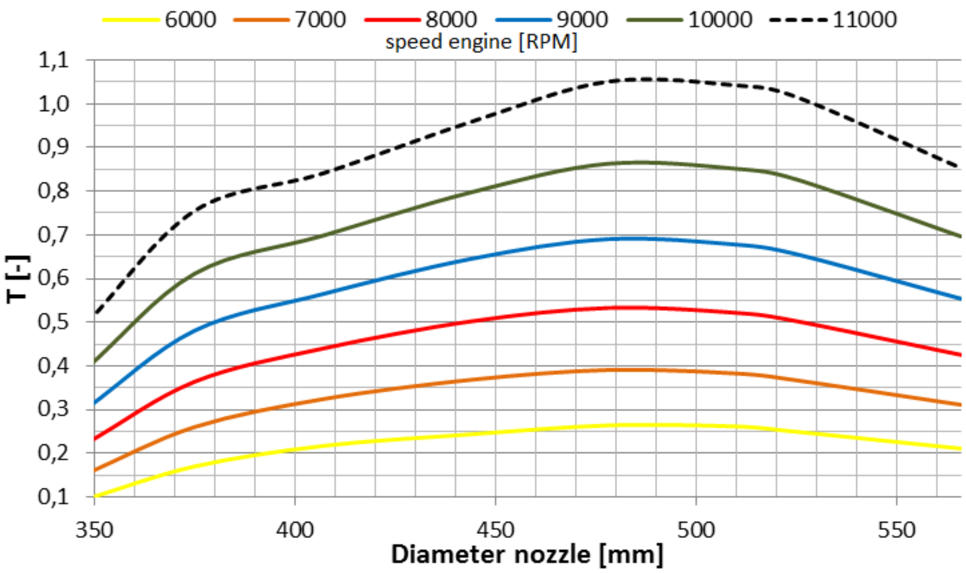

FIGURE 7. Dimensionless thrust at various engine speeds, depending on the diameter of the exit nozzle.

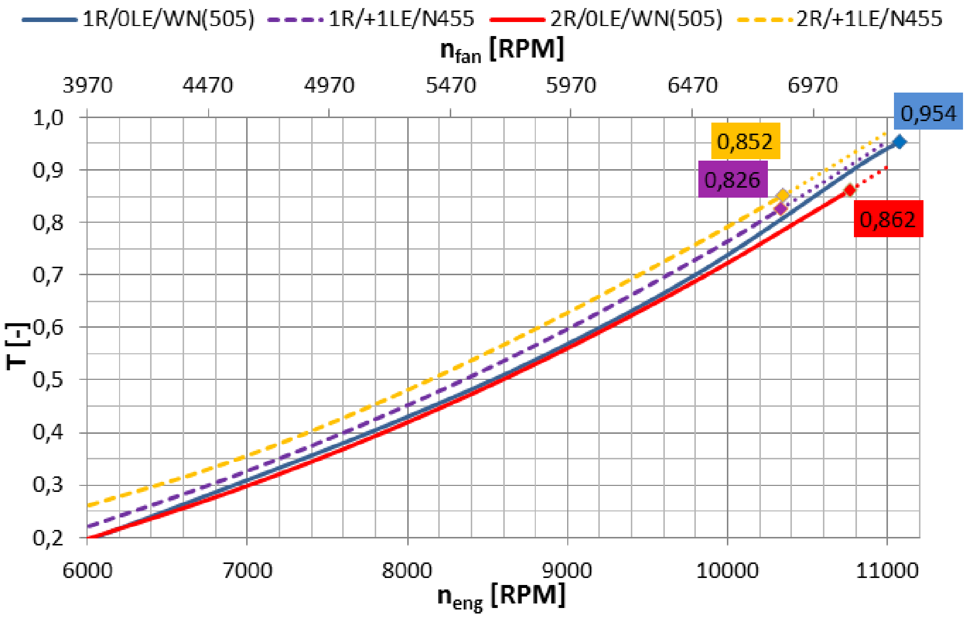

FIGURE 8. Comparison of the use of one radiator and two radiators.

4.2. Measurements with a straight outlet channel

A straight outlet channel, referred to as Apollo for the purposes of our work, is an attachable segment of duralumin sheet and flanges for mounting to a part of the rotor and to hold the nozzle, which is made of the same material, see Fig. 5.

Fig. 6 shows the results for thrusts measured using output nozzles of various diameters[1]. The selection of the nozzle size has a strong influence on the size of thrust. The highest levels were achieved when using a nozzle with a diameter of 478 mm.

In the course of the measurements there are not only various values of the polynomial equations showing the character of the regression characteristics, but also various maximum engine speeds/fan speeds. Maximum speed is achieved at about 10200 to 10800 engine revolutions per minute. The dashed curve represents the theoretical part of the continuation of the performance characteristics.

Fig. 7 shows that the most suitable nozzle diameter for static thrusts is around 500 mm, which corresponds to the annular area of the rotor blades.

4.3. Measurements with a shaping outlet channel

Comparison of the configuration for one radiator and for two radiators. A comparison of the thrust characteristics using one radiator and two radiators in the bypass channel in the outlet channel

[1] The values are given in dimensionless form because the work is ongoing as a part of project MPO ČR FR-TI3/527 “Ultralehký letoun s dmychadlovým pohonem” (Ultralight with a ducted fan)

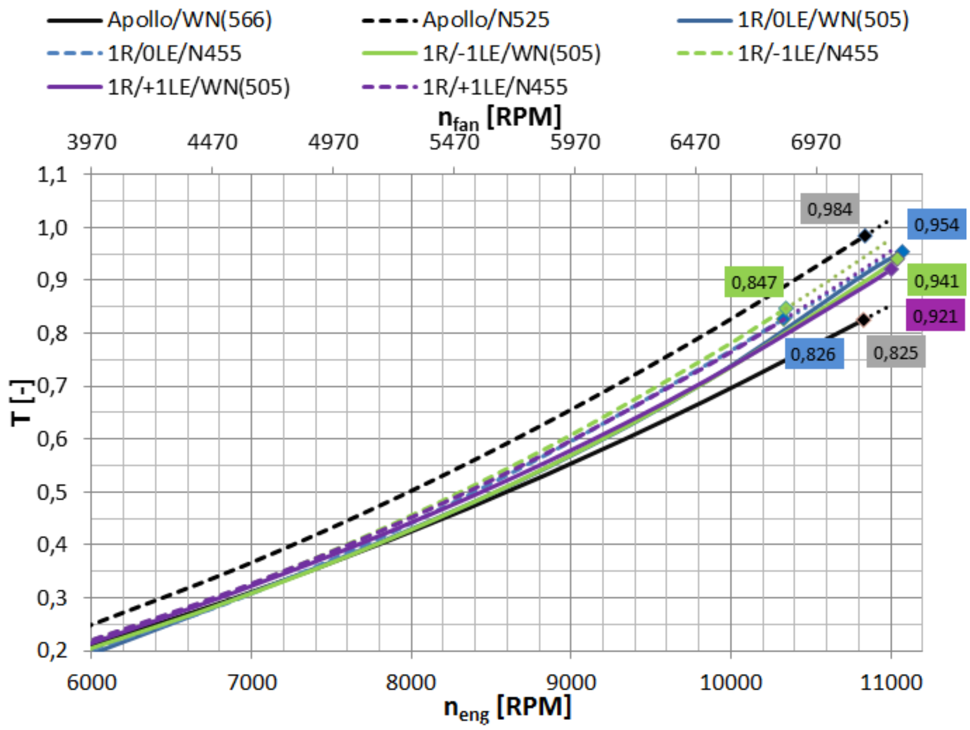

Figure 9. Dimensionless thrust, depending on the engine speed/fan speed for various configurations with one radiator.

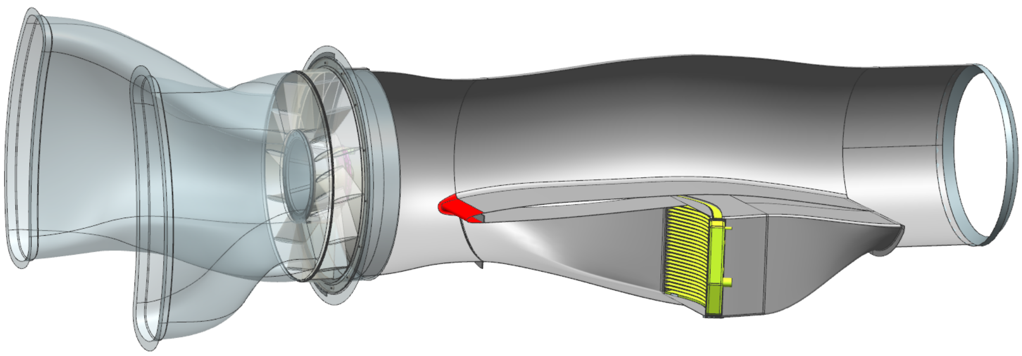

Figure 10. View of the leading edge of the outlet channel (red).

is shown in Figure 8. Measurements of both variants without the nozzle provide information about a slight decrease in thrust throughout the entire speed range of the drive. This is due to a higher pressure loss in the cooling bypass. However, when the measurement is made with a nozzle (diameter 455 mm), higher thrust values are measured in the arrangement with two radiators. This is probably due to the higher heat flow energy obtained using two radiators behind each other. This is then converted to kinetic energy.

Higher thrust, possibly generated by the use of two water radiators, is not advantageous for the flight propulsion unit, due to the greater weight and complexity of the system.

Measurements with one radiator. The one-radiator arrangement was selected for subsequent development of the drive based on the above measurements.

Fig. 9 shows the thrust curves for three values of the leading edge of the outlet channel in the range of approximately 0°, +10° and −10° and configuration both without a nozzle and with a nozzle with a diameter of 455 mm. The limits for the rotation of the leading edge are the maximum possible for this structure. The results that are compared are related to two characteristic measurements with a straight outlet channel.

Generally, during all measurements without nozzles, the maximum engine speed was achieved at 11000 RPM (the maximum speed of an unloaded motor is 13500 RPM). When using the nozzle, the maximum speed due to throttling the flow is roughly equal to 10350 RPM. The dotted curves therefore represent a theoretical continuation of the performance characteristics.

Each measurement shows that the position of the leading edge separating the cooling air from the main

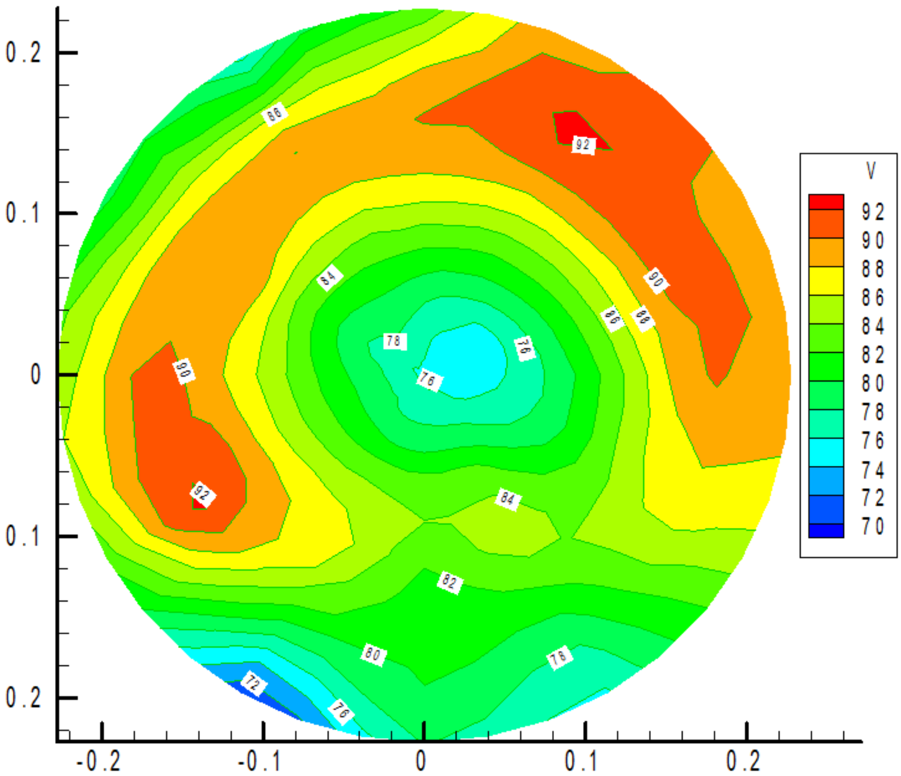

FIGURE 11. Velocity field in the nozzle.

flow does not in practice have a significant effect on the magnitude of the thrust of the propulsion unit.

In the case of measurements without nozzles, higher thrust of the order of 0.95 at about 11000 RPM is achieved in static modes. The use of a nozzle, in our case with a diameter of 455 mm, provides a higher thrust directive describing the dependence of the thrust on the engine speed, while achieving the above-mentioned lower absolute speed values. The result is thrust of the order of 0.85 at about 10350 RPM.

4.4. VELOCITY AND TEMPERATURE FIELDS OF THE AIR DUCT

In addition to searching for the thrust characteristics, we also measured the pressure, or the velocity field, on the output side of the air duct in the nozzle (Fig. 11). This experiment was intended to find out whether the flow through the cooling by-pass reaches the output speed of the mainstream, and the total velocity distribution in the mainstream.

Figure 11 below shows that the velocities on the output side of the air duct are not compensated, and that the lower portion belonging to the outlet bypass achieves lower levels of final velocity. The flow re-accelerated to about 90 % of the main stream, which will result in some increase in the final loss of flowing air. Uneven air flow through the main channel can also be observed. This is caused by the tangential speeds at the rotor.

The displayed temperature field behind the radiator (see Fig. 12) shows non-uniformity caused by a one-sided intake of heated coolant from the engine, which is cooled in the flow through the radiator to the left (in the direction of flight). Due to non-uniformity of the coolant flow in and out of the radiator the uniformity of the fluid flow in the by-pass cannot be seen in this figure.

For any subsequent computer simulation of the flow using CFD programs to verify the computational model, the most important data will be the static thrust values, the speed and the pressure flow field image at the output nozzle, and the temperature field at the radiator. Of course, the conditions in which the experiment was conducted have to be taken into account.

4.5. THE OPERATING PARAMETERS OF THE PROPULSION UNIT

Other measured operation parameters of the drive include the inlet and outlet temperature of the radiator(s), the temperature of the water coming from the oil heat exchanger, the temperature in the bearing of the rotor, the temperature of the exhaust manifolds at the place of connection (below the engine), as well as the mass flow of the engine coolant and the liquid from the oil-water heat exchanger, the fuel consumption, etc.

Table 1 shows some of these parameters at various drive configurations and at a longer operating time — the hold of this mode is about 10 minutes sufficient engine heat has been reached. A more stable thermal balance than for the short-term measurements can be proved.

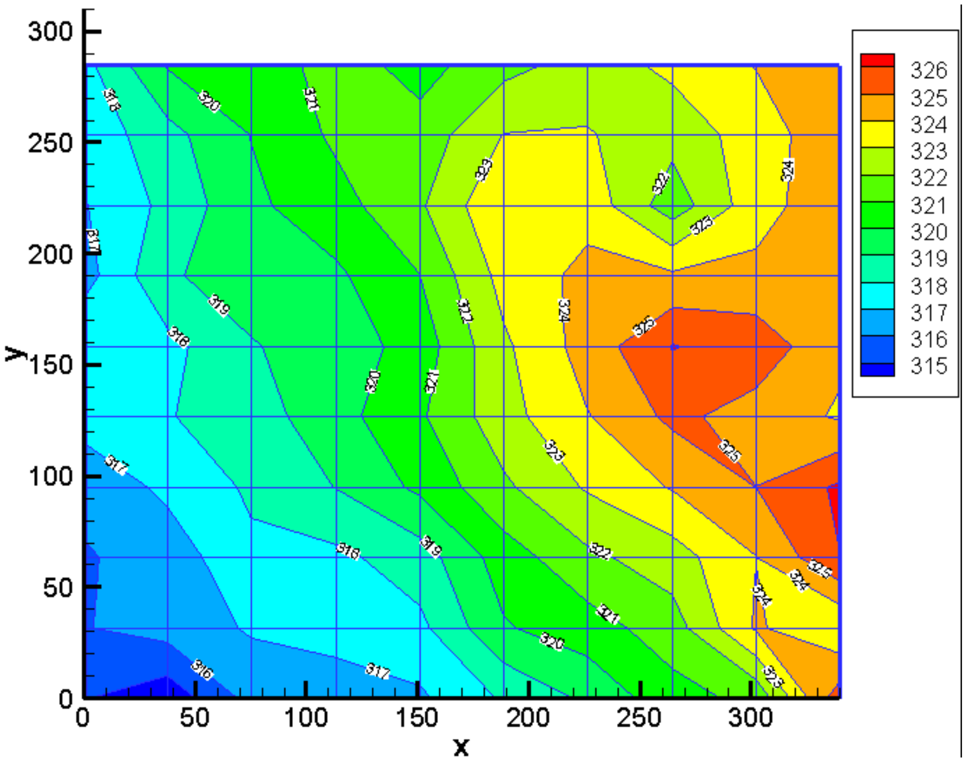

Figure 12. Temperature field behind the radiator.

Values given with a '+' sign indicate that this value continued to increase if the program was not stopped.

If two radiators are used, the heating area is twice as large as when a version with one radiator is used. Theoretically, there is a higher temperature gradient, but the results indicate that this does not in fact occur in reality. The reason for this is probably the higher pressure loss of the two radiators, which will reduce the flow in the by-pass.

It can be deduced from the values that are obtained that even the settings of the leading edge do not confirm the original assumption that opening the cooling bypass should cool the engine coolant more, and closing the cooling bypass should cool the engine coolant less. On the contrary, it was found that when the leading edge is deflected in both directions, it achieves a 15 % decrease in the cooling effect in comparison with the basic aerodynamically clean zero distributing leading edge (Fig. 10).

5. Conclusion

Measurements of the thrust characteristics have provided an answer to the question of how many radiators to employ: the arrangement with one radiator is better. This option will have a positive effect by reducing the weight of the aircraft cooling system. In addition, the results show that the angle of the leading edge separating the cooling air from the main stream does not affect the magnitude of the thrust of the fan.

The designed shaping outlet channel with a radiator of this concept and with this geometry achieved approximately 90 % of the theoretical maximum thrust of the straight channel at an engine speed of 11000 RPM. If the real achieved terms are considered, we receive equivalent results, more precisely we achieve 97 % of the maximum thrust of the straight channel.

It can also be stated that the fan blading, which was been calculated in a static mode and for a design speed of 11500 RPM engine (or 7606 RPM fan), was not achieved and cannot be achieved under the current circumstances. It would be useful for subsequent work to recalculate the blading in order to achieve the predicted values and higher usable performance. According to the regression equation describing the thrust characteristics, the thrust for the designed speed of the fan, in the case of a shape channel, would reach about 1.05 (for a straight outlet channel, the value would be 1.15).

A number of problems arose during the development of this type of aircraft that we do not face when developing a "regular" ultralight. They require a nontraditional or completely new solution of aerodynamic, structural and technological factors.

We are currently working on equipping the demonstrator fuselage with a fully functional new BMW S1000RR power unit, with which the final measurement of a new drive will be made.

List of symbols

m weight [kg]

m' mass flow rate [kg m^{-3}]

n_{eng} engine speed [min^{-1}]

n_{fan} fan speed [Pa]

p measured pressure [Pa]

n_{eng} [RPM]	T [°C]							m' [kg/s]	
Variant configuration with 2 radiators									
	before radiators	between radiators	behind radiators	heat oil	ambient air temp.	rotor bearing	exhaust manifolds	engine cooling	heat oil
10250	69.4	61.3	58.6	–	16.5	83.3+	778.5+	0.55	0.23
10250	68.7	61.4	59.4	–	16.5	80.2+	786.5+	0.54	0.25
10450	62.1	56.5	52.6	–	13.4	75.3+	804.7+	0.55	0.22
11000	62.9	59.2	53	–	15.2	78+	814	0.63	0.23
Variant configuration with 1 radiator									
	before radiators		behind radiators	heat oil	ambient air temp.	rotor bearing	exhaust manifolds	engine cooling	heat oil
11000	78		64.8	80.4+	17 (19)	79+	819.5+	0.66	0.27
11085	81.4		66.2	84.5	17 (18)	86+	832+	0.61	0.23

TABLE 1. The measured operating parameters.

p_0 ISA base pressure ($H = 0\,\mathrm{m}$), $p_0 = 101325\,\mathrm{Pa}$ [Pa]
T thrust [–]
T measured temperature [°C, K]
T_0 ISA base temperature ($H = 0\,\mathrm{m}$), $T_0 = 288.15\,\mathrm{K}$ [°C, K]
V volume [m^3]
δ relative pressure [–]
θ relative temperature [–]

List of abbreviations

DOHC — Double Over Head Camshaft
PS — Metric horsepower — an older unit of power, used in Europe
ISA — International Standard Atmosphere
Apollo — Straight outlet channel (work title)
0LE — Configuration with zero angle of the leading edge (normal)
+1**LE** — Configuration with a positive angle of the leading edge (by-pass more open)
−1**LE** — Configuration with a negative angle of the leading edge (by-pass more closed)
1R — Configuration with one radiator
2R — Configuration with two radiator
CFD — Computational Fluid Dynamics
N — Configuration with nozzle
RPM — Revolutions per minute
WN — Configuration without nozzle

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