Tests of the propulsion unit of an unconventional ultralight aircraft

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Abstract

This paper deals with static tests of the demonstrator of a new engine for the category of ultralight and small sport aircraft. Used laboratory stand for the fan drive allows the comparison of different construction solutions. The purpose of these tests was to verify the functionality of the drive, the measurement procedure and to compare the individual obtained propulsion system results. Realized experiments focused primarily on determining the available thrust of the new engine, its dependence on the engine speed, the view of the velocity field in the output of air duct while at the same time ensuring the necessary cooling of the engine and data acquisition for subsequent design optimization.

Abstrakt

Příspěvek se zabývá statickými zkouškami demonstrátoru nové pohonné jednotky pro kategorii ultralehkých a malých sportovních letadel. Použitý laboratorní stand ventilátorového pohonu umožňuje porovnání různých konstrukčních řešení. Účelem těchto zkoušek bylo ověření funkčnosti pohonu, postupu měření a porovnání získaných výsledků propulzního systému mezi sebou. Realizované experimenty se zaměřily přede vším na určení využitelného tahu pohonné jednotky, její závislosti na otáčkách motoru, pohled na rychlostní pole ve výstupní části proudovodu při současném zajištění potřebného chlazení motoru a získávání dat pro následnou optimalizaci konstrukce.

Key words

Propulsion unit, laboratory stand fan drive, static thrust, available thrust.

Note: The values are mentioned dimensionless due to the ongoing work and following the project MPO ČR FR-TI3/527 "Ultralight with a ducted fan."
Pozn.: Vlastní hodnoty tahů jsou uvedeny bezrozměrně z důvodu pokračujících prací a návaznosti na projekt v programu MPO ČR FR-TI3/527 „Ultralehký letoun s dmychadlovým pohonem“.

1. Introduction

A large majority of ultralight aircrafts use the propeller drive. Besides this dominant mode of energy conversion to gain thrust there are:

- Rotating blade (helicopter).
- Nonstandard configuration propeller - propeller in pusher configuration or in a ring.
- Ducted Fan / Cold Jet
- Jet engine

Considering the possible creation of a new category of ultra-lights (airplanes to 450 kg) and at the same time complying to certification regulations (no jet engine) the alternative drive fan can be used.

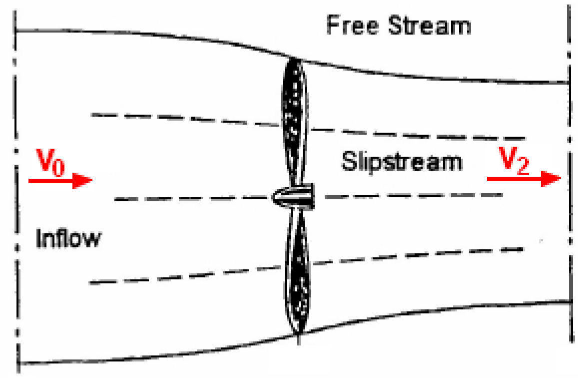

Fig. 1 – Propeller

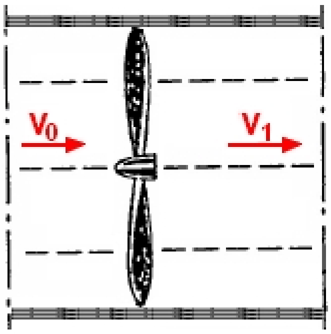

Fig. 2 – Propeller in a ring

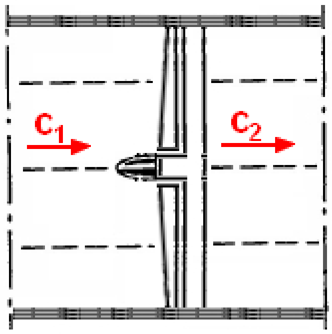

Fig. 3 – Blade stage

$$\eta_v = \frac{v_0}{v_0 + \frac{1}{2} \cdot v_2} \qquad (1)$$

$$\eta_{vp} = \frac{2 \cdot v_0}{v_0 + v_1} \qquad (2)$$

$$\eta_{ls} = \frac{2 \cdot c_1}{c_2 + c_1} \qquad (3)$$

Comparing the effectiveness of the three selected models suggests that the propeller in the ring and blade stage have a higher propulsive efficiency compared to conventional propeller (see Equation 4). The ratio is higher than 1 and at zero forward speed it is actually equal to 2. Of course it is the asymptote of the states and the actual values will be lower. However, there is a physical substance, which outlines the nature and meaning of the idea to use another drive.

$$\frac{\eta_{vp}}{\eta_v} = \frac{2 \cdot v_0}{v_0 + v_1} \cdot \frac{v_1}{v_0} = \frac{2 \cdot v_1}{v_0 + v_1} \qquad (4)$$

In the past, a number of aircrafts were constructed attempting to use either a ducted fan or a propeller in a ring. In most cases, these were amateur efforts with insufficient theoretical support, or with inadequate financial support, and in the end they were unsuccessful.
The technical possibilities that have become available in recent years, especially the existence of relatively light and highly effective high-speed engines and significant developments in composite technologies, have enabled the construction of an airplane of this type under conditions accessible to producers of ultralights.

2. Description of propulsion unit

This is a type of construction bordering between a propeller and jet propulsion where such 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.

The development and subsequent use of fans logically brings a number of technical problems, however, under certain circumstances they can be expected to bring higher flight performance, greater safety and security.

2.1 Engine of propulsion unit

The core of the stand contains the earlier choice of power unit – the four-stroke inline four-cylinder engine from the Yamaha R1 model 2004 sports bike. Stroke volume is 998 cm^3 and the power on crank shaft is 131.4 kW (179 PS) at 12,500 revolutions per minute (RPM). 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 at the other end attached to the rotor stage.

Fig. 4 *– Engine Yamaha R1*

This engine was chosen for the construction of the test stand because of the then favorable power / weight ratio. Weight is a limiting factor in the development of ultralight aircraft.

2.2. Ducted fan power unit

The air duct consists of inlet channels, single-stage low-pressure axial fan with stator stage, in this case located in front of the rotor stage, and the outlet channel with a nozzle.
The Fig. 5 shows a schematic drawing of the drive from which all its parts can be seen.

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, for creating a suitable outlet flow then entering the rotor blades driven by a piston engine. The complete geometry is theoretically designed so that the design only has the 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 in the end of the drive and a portion of the air is streamed throuhg the bottom bypass throuhg the radiator of the engine. Coolant bypass is designed to minimize the pressure loss resulting from the aerodynamic drag of the cooler. Both branches of the outlet channel are then reconnected before the output nozzle.

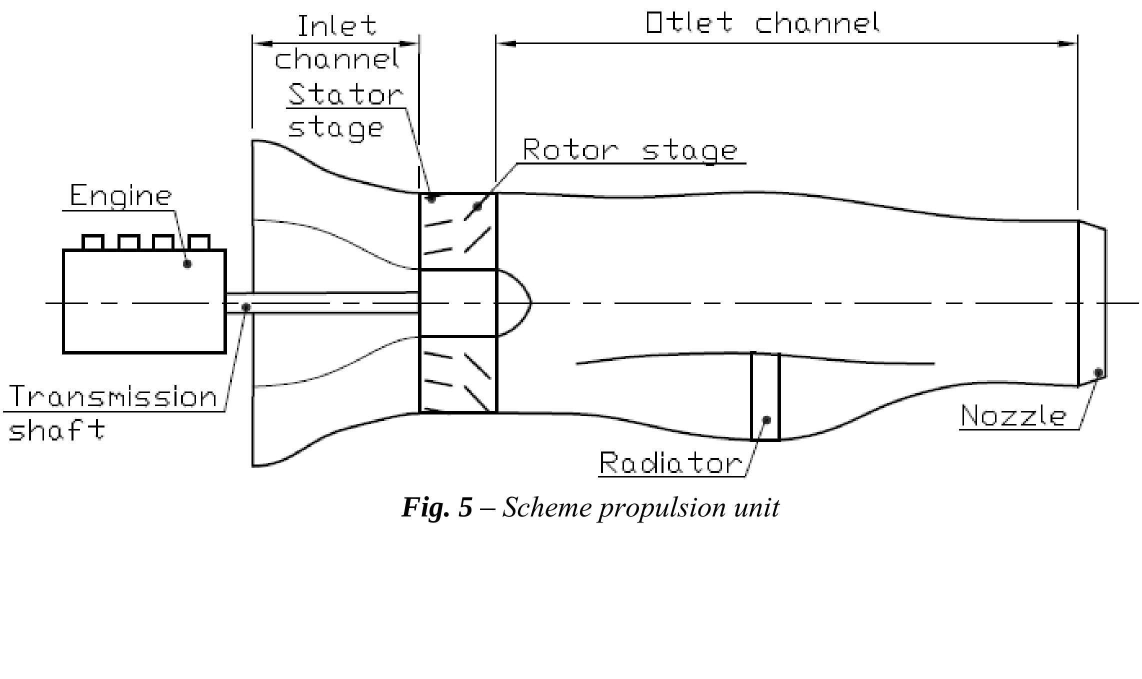

Fig. 5 *– Scheme propulsion unit*

3. Experimental facility

One of the necessary and logical steps for the successful development of the new concept aircraft was building a testing stand for the engine. The stand designed for static measurements (at zero forward speed) in laboratory conditions is, besides for verification of the system´s proper functionality, designed to experimentally determine the static thrusts characteristics for different configurations of the propulsion unit.

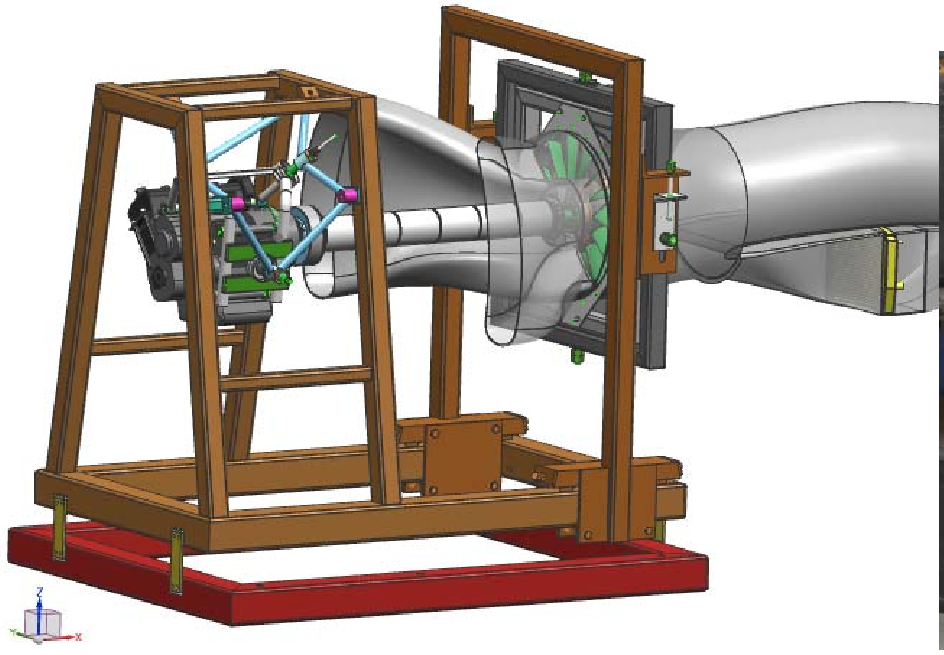

Fig. 6 *– Model of laboratory stand*

Fig. 7 *– Strips with strain gauges*

Demonstrator consists of a frame, engine and the propulsion unit. The frame is composed of three parts, the upper part of the frame (see Fig. 6, brown and red) serves to hang up the engine, the electrical instalation and the airplane drive. The two sections of the demontrator frame are connected by four accurate metal strips equipped with strain gauges. Direction of thrust acts in the direction of minimum stiffness of the strips.

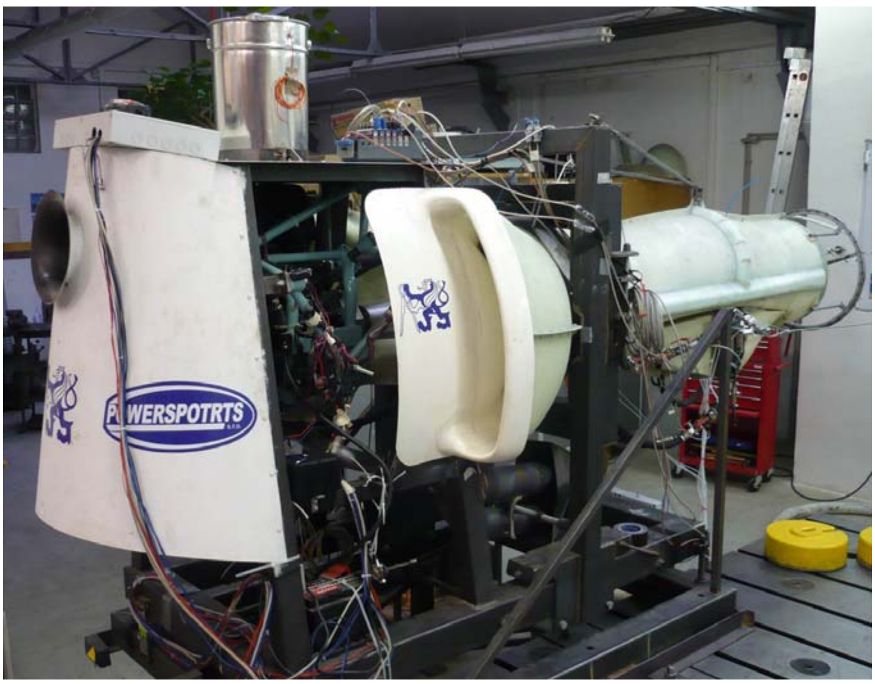

Fig. 8 *– Static test stand for the power unit in the laboratory*

The third, lower part of the frame (Fig. 9) is an essential part permanently attached to the ground. The top frame has the possibility of longitudinal movement towards the lower frame with ball bearings. This arrangement allows for measurement of thrust using the connected dynamometers. Due to the strain gauge full bridge installed on each metal strip thrust can also be measured during operation of the power unit after proper calibration.

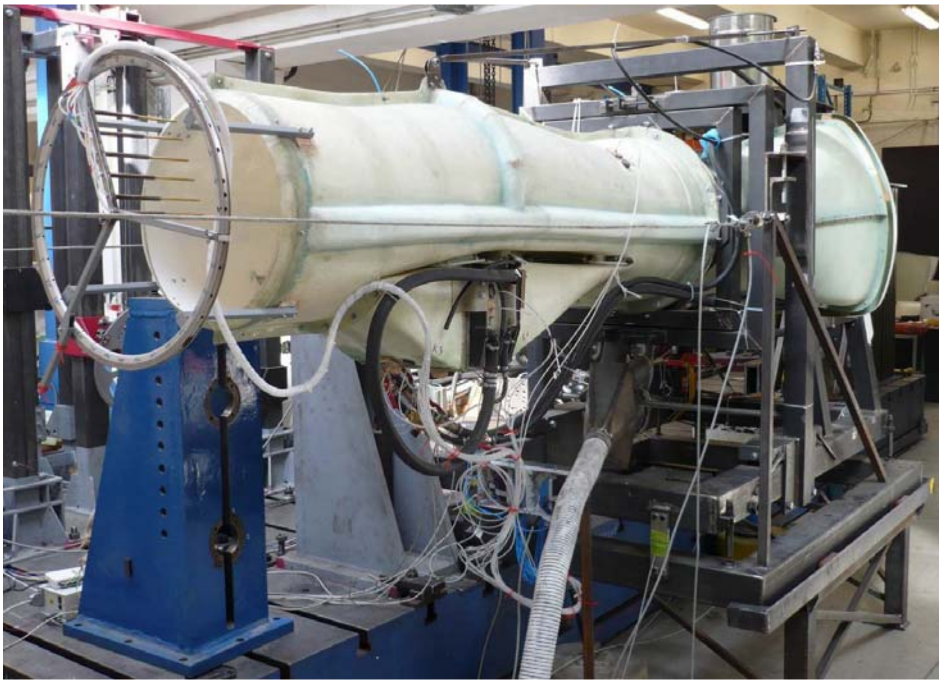

***Fig. 9** – Rear view of the test equipment to measure the performance characteristics*

4. Goal of measuring

Sufficient available thrust is the basic requirement for the future aircraft with the new power unit. Measurements on the demonstrator of the aircraft propulsion unit enables to measure important characteristics of complete propulsion system.

Due to the subsonic flow throughout the propulsor unit the jet field in all its parts interact. Alignment of all the above mentioned components so as to achieve an acceptable level of internal efficiency requires the application of optimization techniques in the design of the entire air duct.

It is a complicated process that have requested and requires extensive theoretical analysis, numerical simulation and execution of experiments. All this is suggested by important requirements such as:

- neccessity to ensure a uniform flow field at the inlet to the fan,
- dimensionally conflicting requirements for the fan (on the one hand, we have mass flow, and the size of the thrust force, on the other we have Mach numbers for the blade ends and the mounting dimensions),
- maximum focus on the resulting weight.

For the above reasons, in this article we will focus on the propulsion measurement for the existing blading and the shape of air duct. To find the appropriate operating conditions different combinations of propulsion were tested. Configuration with two and one radiator located in the channel was selected as well as position of the leading edge dividing the air flow in the outlet channel in two ways and variations of different nozzles.

The primarily watched data is the thrust of the propulsion unit determined by using dynamometers and metal strips equipped with strain gauges dependant on the engine speed, hence the fan. Furthermore, the velocity, respectively the pressure field on the outlet nozzle was determined, from which the ability to approach the stream flowing through the by-pass of the main stream can be deduced. Smooth reunion of these two streams will have a significant effect on the secondary flow and its energy loss. Among other significant parameters from the operational point of view there are the inlet and outlet temperatures of radiators and the amount of heat energy transmitted by the flow, the temperatures in the rotor bearings, exhaust, engine compartment, voluminal flow of coolant and oil heat exchanger, fuel consumption and more.

These values can further be compared with the theoretical computational values of the propulsion unit or of the computer CFD simulation.

5. Components of Test Stand

To measure the comparative characteristics of different configurations of the driving set-up there are dynamometers (HBM HBM U2B/10kN and U2AD1/500kg) and strain gauge force sensors installed in the air duct axis on the test stand. Engine speed, respectively transmission shafts are measured using electrical impulses from the control unit, which were compared using non-contact optical sensor.

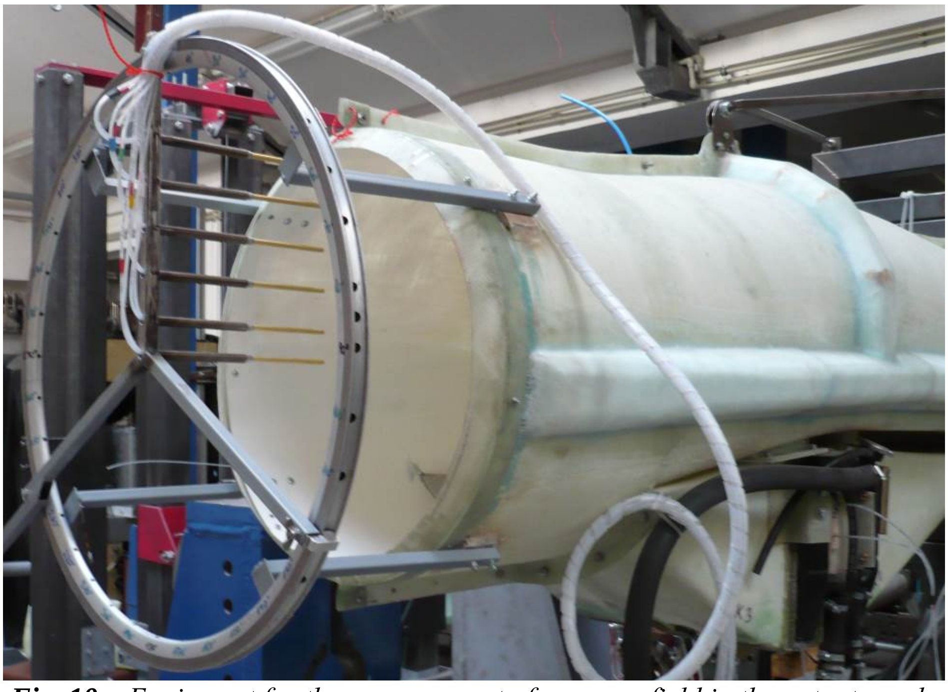

Fig. 10 *– Equipment for the measurement of pressure field in the output nozzle*

In the back of the outlet channel there is a device for the attachment and movement of six pitot-static probes in the flow field. This sample is intended to measure the velocity and pressure fields of a circular shape with diameter of 500 mm. Connecting the probes with pressure tubing with pressure transmitors and sensor DCP DP1 (Fig. 12) is a part of this set-up.

Several delivery points of total and static pressure are located in the main channel, in front, behind or between the radiators.

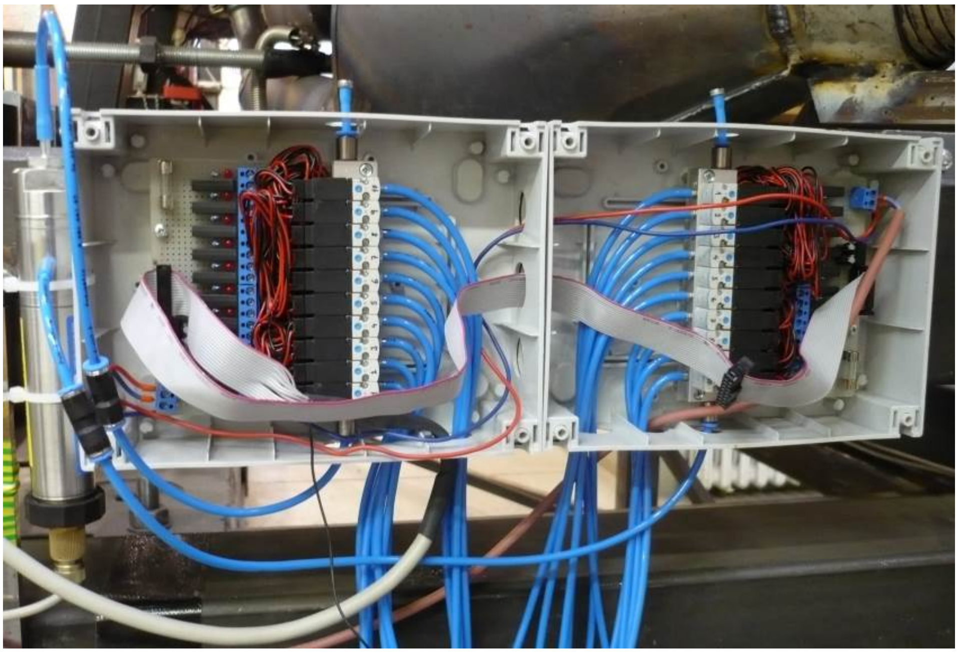

Fig. 11 and 12 *– Pressure switch with pressure sensor DCP DP1*

The amount of energy transmitted to the engine by the radiator is recorded by the flow indicators of the coolant and fluids from oil-water heat exchanger, as well as their input and output temperatures.
Stand includes the deployment of additional thermocouples in place of exhaust gas bearing rotor and in the place behind the radiator using a set of two adjustable and removable temperature control rods (see Fig 13).

Fuel consumption when running the engine is measured by weight loss of gasoline, whent its density is known.

Fig. 13 *– The equipment for measuring temperature field at the radiator*

6. Data acquisition and monitoring

Data management and acquisition was performed with CompactRIO platform from National Instruments.

This device is suitable for Real-Time applications of different types, due to its wide modularity and options for individual configuration by the user.

Programming of the device was done using measurement applications created in the graphical programming language LabView, also from National Instruments.

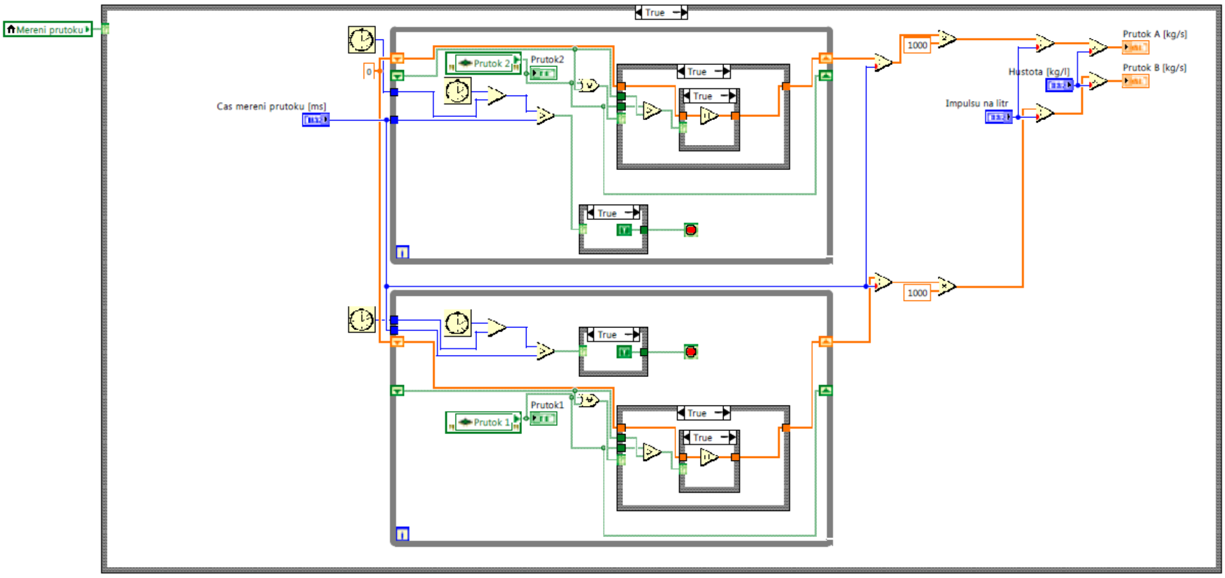

Fig. 14 *– Sample part of the block diagram - cooling water flow measurement*

For the actual measurements of the demonstrator measuring cards were used - modules NI 9403, 9213, 9237 (2x), 9215 and 9401.

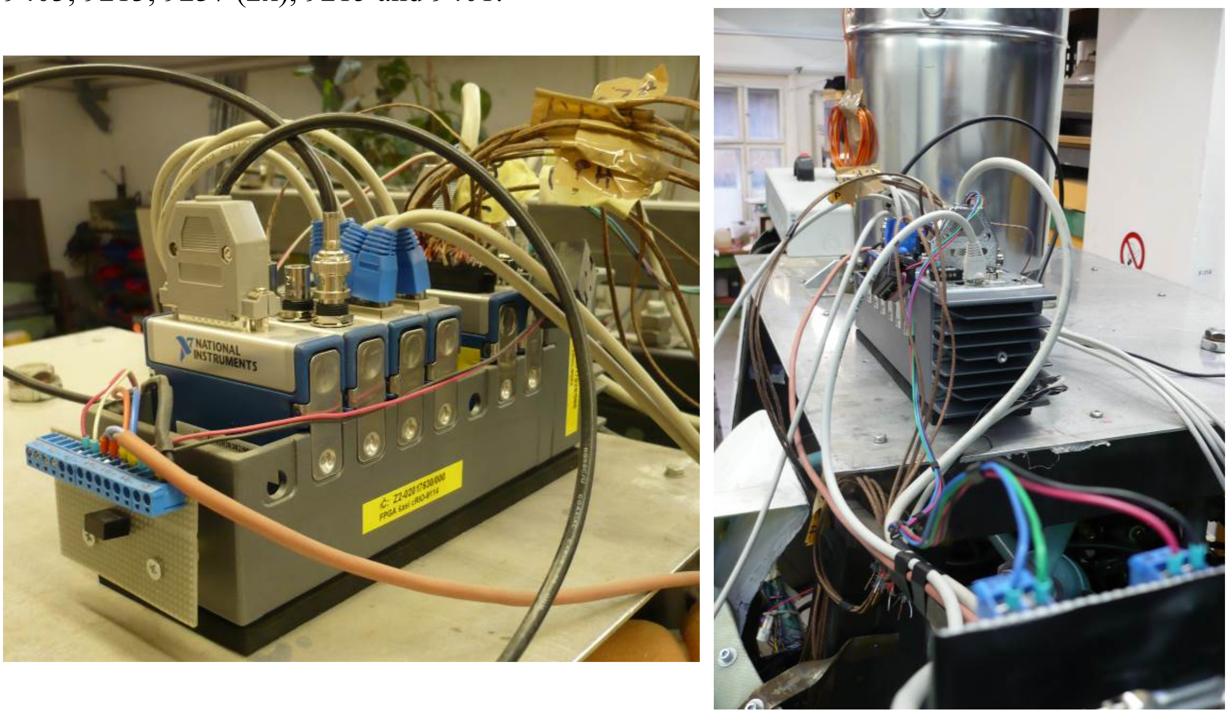

Fig. 15 and 16 *– CompactRIO with measuring card*

7. Measurement results

For comparison and verification of the suitability of individual drive configurations (one / two radiator arrangement with output nozzle and angle of the leading edge dividing the flow in the outlet channel) measurements were taken of the ventilator unit with direct outlet channel, see Fig. 17 (work title Apollo).

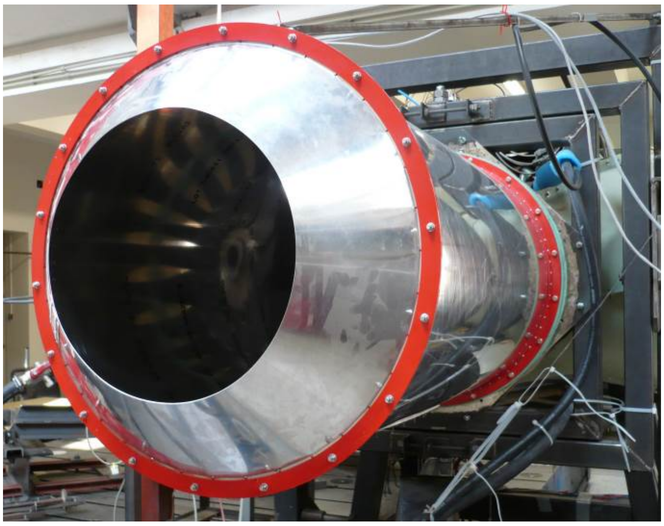

Fig. 17 – Measurement of *straight outlet channel*

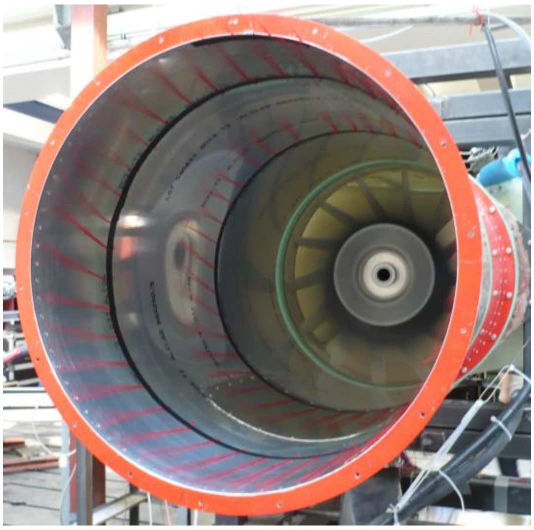

Fig. 18 *– The tangential velocity field behind the rotor stage*

Fig. 19 shows the results of thrusts measured using different diameter outlet nozzles. Selection of a nozzle size strongly influences the size of thrust. The highest levels were achieved when using a nozzle with a diameter of 478 mm. Fig. 20 shows that the most suitable diameter of the nozzle for static thrusts is around 500 mm, which corresponds to the annular area of rotor blades.

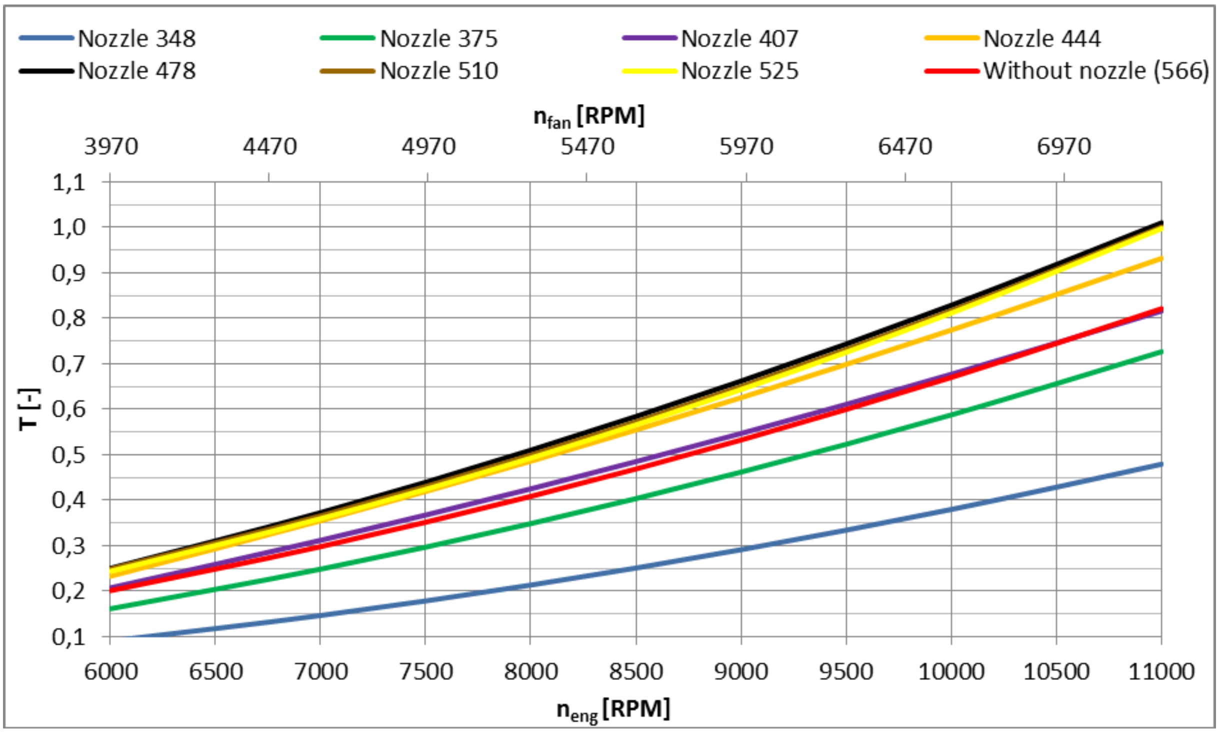

Fig. 19 *– Dimensionless trust, depending on the engine speed, resp. speed fan (chosen nozzle number corresponds to its diameter)*

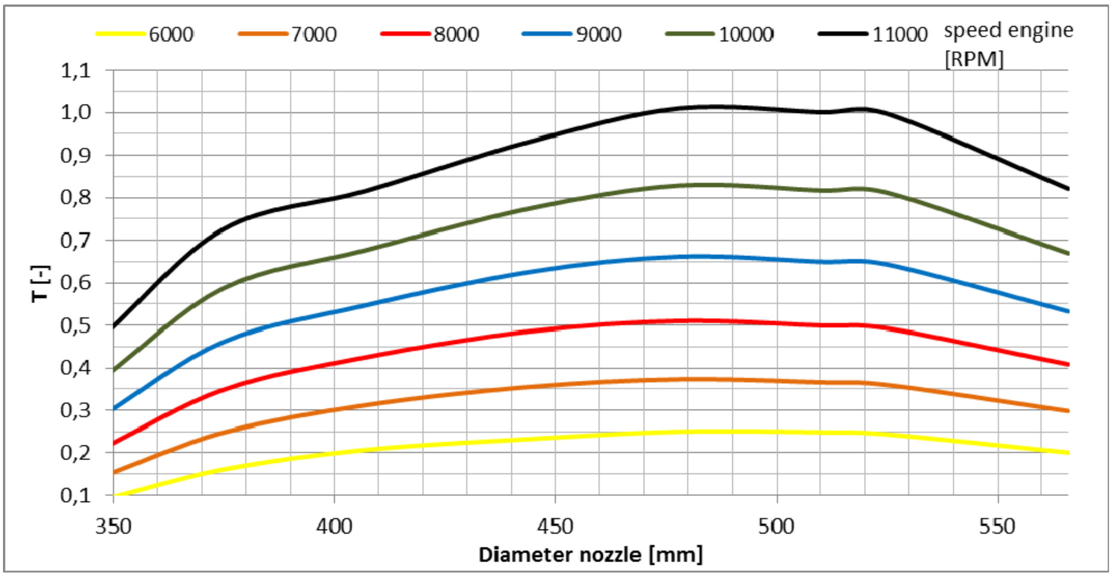

Fig. 20 *– Dimensionless thrust at various engine speeds, depending on the diameter of the exit nozzle*

List of abbreviations for greater clarity in this chapter:

0LE	Configuration with zero angle of the leading edge (normal)
+1LE	Configuration with a positive angle of the leading edge (by-pass more open)
-1LE	Configuration with a negative angle of the leading edge (by-pass more closed)
1R	Configuration with one radiator
2R	Configuration with two radiator
N	Configuration with nozzle
WN	Configuration without nozzle
Apollo	Straight outlet channel (work title)

Demonstration comparing the use of one and two radiators in the outlet channel provides information about the course of the decrease in thrust throughout the speed range of the power unit. The reason is the higher pressure loss in the cooling bypass that exceeds the higher heat energy gain when using two radiators behind.

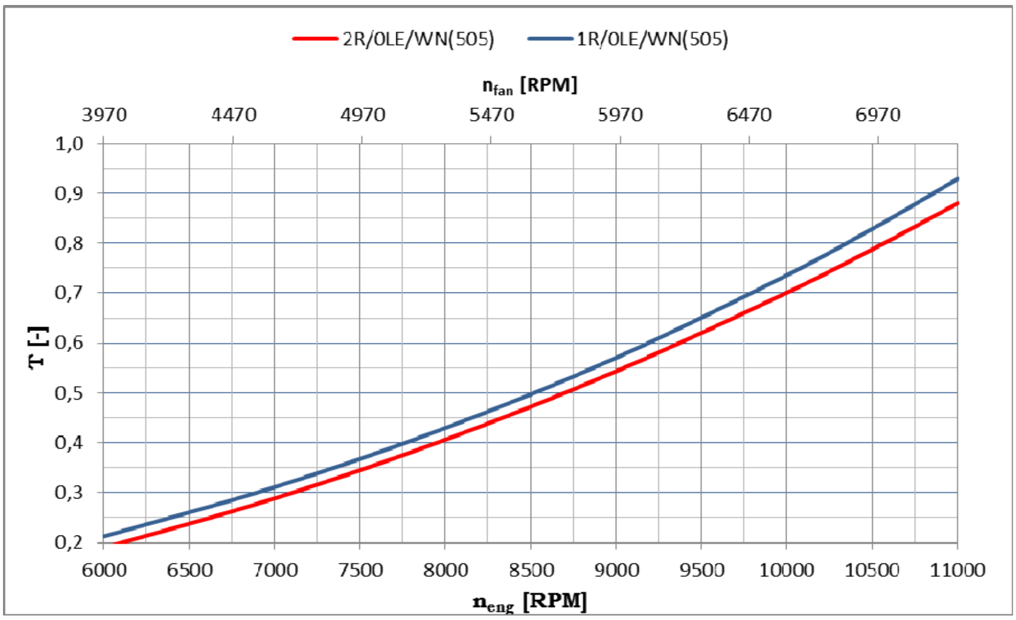

Fig. 21 *– Comparison of the use of one and two radiators*

***Fig. 22** – A by-pass with a two radiators*

***Fig. 23** – A by-pass with a single radiator*

If a fan drive is used, the pressure energy of the air flow developed by the rotor blades and subsequently in the outlet channel equipped with a nozzle is converted into kinetic energy. Thus both the rotor and the outlet channel serve to generate thrust.
One radiator arrangement was selected from the above measurement. It was therefore decided to do a more complex measuring of the characteristics of the drive with one radiator. In terms of comparison, and credibility the measurement was made on the same day, and especially at the same ambient temperature.
Fig. 24 shows 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 results compared are related to two characteristic measurements with a straight outlet channel.

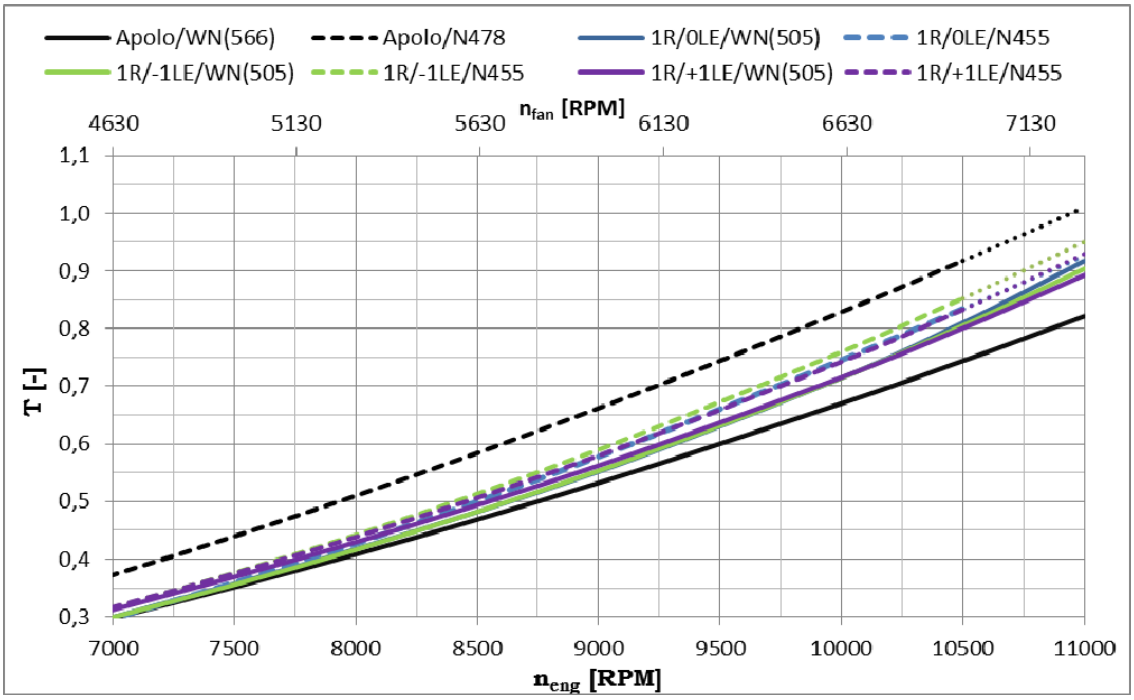

***Fig. 24** – Dimensionless thrust, depending on the engine speed, respectively fan speed for different configurations with one radiator*

Generally, during all measurements in the absence of nozzles the maximum engine speed was achieved at 11,000 RPM (maximum speed of an unloaded motor is 13,500 RPM). When using nozzles max speed roughly equals to 10,500 RPM. Dotted curves therefore represent a theoretical continuation of the performance characteristics.

The velocity field at the output nozzle was measured. The Fig. 25 shows that the velocity compensation at the output section is not achieved (lower section of lower velocity values belongs to the output of by-pass), which will lead to an increase in the final mass flow losses. The uneven air flow through the main channel caused by the tangential velocities behing the rotor can also be seen.

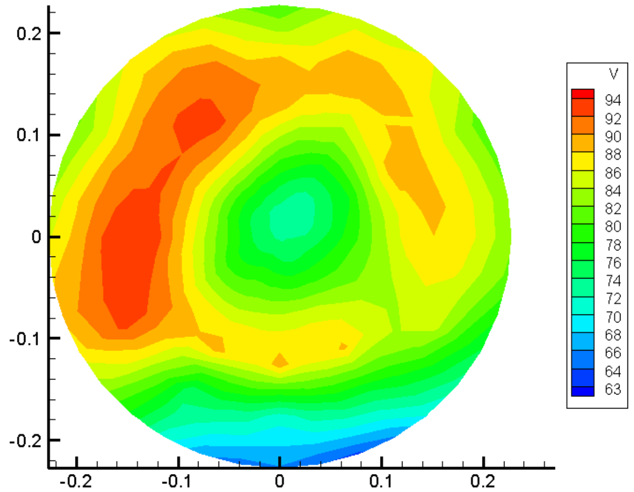

***Fig. 25** – Velocity field in nozzle*

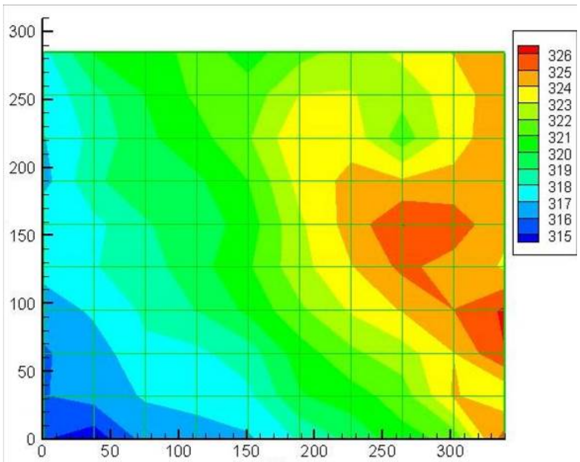

***Fig. 26** – Temperature field behind the radiator*

The displayed temperature field behind the radiator (see Fig. 26) shows the non-uniformity caused by one-sided intake of heated coolant from the engine and it can indicate the uniformity of the flowing medium.

8. Conclusion and Future Work

Thanks to measuring the question of the number of radiators has been answered and the choice of one radiator arrangement was made. It is evident from the results that the angle of the leading edge does not significantly affect the thrust of the drive unit (Fig. 24). On the contrary, in operation the angle does have a significant influence on the thermal balance of the engine.

The proposed outlet channel with mounted radiator reaches 90% of the theoretical maximum thrust of the straight outlet channel at engine speed 11,000 RPM. In case of practically measured values we get equivalent results.

A number of problems have arisen during the development of this type of aircraft that we do not face when developing a "regular" ultralight, and which require a non-traditional or completely new solution of aerodynamic and structural and technological aspects.

But we can say that after a rigorous computer simulation flow using CFD programs and their verification with experimental data and theoretical values a lot of questions can be answered for the implementation of subsequent measures to increase the efficiency of the drive.

Although measurements on a propulsion demonstrator on the laboratory stand provided a number of very valuable performance and operational information, for the further development of a new airplaneit is necessary to find out performance characteristics of the propulsion unit dependant on the airspeed. For this reason it is necessary to perform the mobile tests of the propulsion unit.

Currently the team is working on equipping the fuselage demontrator with fully functional propulsion unit with which the expected final measurements will take place in the aerodynamic tunnel. Parallel the correction coefficients will be ready to convert values measured in the tunnel for movement in the free air stream.

A direct application of the aircraft for which there is a new propeler unit developed is shown in Fig. 27 and 28.

***Fig. 27** – UL-39 aircraft*

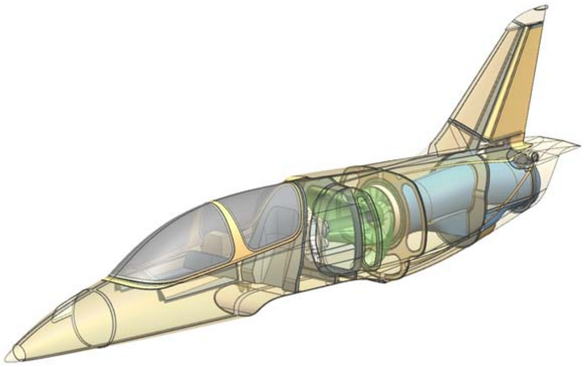

***Fig. 28** – Location of propulsion system in the fuselage*

Symbols

v_0, c_1	Input velocities	[m.s^{-1}]
v_1, v_2, c_1	Output velocities	[m.s^{-1}]
η_v	Propeller efficiency	[-]
η_{vp}	Propeller efficiency in the ring	[-]
η_{ls}	Blade stage efficiency	[-]
T	Thrust	[-]
n_{eng}	Speed engine	[RPM]
n_{fan}	Speed fan	[RPM]

List of abbreviations

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+1LE	Configuration with a positive angle of the leading edge (by-pass more open)
-1LE	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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