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# Experimental verification of performance of tip-jet helicopter propulsion system

Nenad Kolarević [a,*], Stevan Crnojević [b], Miloš Stanković [a], Nenad Latković [b], Marko Miloš [a]

[a] University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia
[b] EDePro.o.o., Kralja Milutina 33, Belgrade, Serbia

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ABSTRACT

This paper presents the methodology for estimation of power delivery and efficiency of the tip-jet helicopter propulsion system. The main advantage of the tip-jet helicopter is the absence of heavy transmission and tail rotor, but if compared to conventional helicopters, it has significantly lower efficiency. The crucial parameter that impacts the performances of the tip-jet helicopter is a propulsion force at the end of the blade. The analytical and numerical calculations with results for prediction of this propulsion force are presented in this paper. The case study is the ATRO-X tip-jet helicopter. Its propulsion system is driven by the gas-generator Phoenix-100, as a power source, which generates propulsion force by ejecting the hot combustion products through the nozzles at the blades tips.

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## 1. Introduction

The tip-jet concept of helicopters implies the creation of the thrust force, as a reactive propulsion force, on the tip of the helicopter blades in the direction which is tangential to the rotor disc. These forces, each for every blade, create the torque that rotates the entire helicopter rotor and conquers the drag. This rotation is used for generating the lift force in order to drive and control helicopter [1,2].

For generating the thrust force on the blades, several devices could be used as power sources. A ramjet or liquid rocket engine can be installed at the blade tip in order to create these propulsion forces. There is only a need for fuel supply which is conducted through the structure of the blades. The Dragonfly is one example of this concept. Some other concepts use the gas generator [3] to produce the operating fluid which is then transmitted through the blades to the nozzles installed on the blade tips. The ejection of this operating fluid creates the thrust force. Based on the temperature of this operating fluid, there are two subtypes of the tip-jet concept: hot and cold cycle tip-jet helicopters. Djinn, a French helicopter, is an example of the cold cycle tip-jet helicopter that successfully flew. The power from the turbo-shaft engine is used to drive the compressor which compresses the air brought through the inlet. This compressed air is used as an operating fluid. ATRO-X helicopter belongs to the group of hot-cycle tip-jet helicopters and its propulsion system is presented in Fig. 1. The gas generator Phoenix-100, which is placed above the rotor head, burns the mixture of compressed air and fuel. The hot combustion products, the operating fluid at around 700 °C, are separated into two branches, one per each blade, with the distributer installed on the gas generator. After passing through the distributer, this mixture is transmitted through the special system of inner channels situated in the blades, which end with the nozzles at the blades tips. The blades are, due to this high temperature, specially designed to be a laser welded construction from Inconel sheet metal [4]. These nozzles are used to create as much as possible of the thrust force, by accelerating the flow and directing it tangential onto the rotor disc. Two flexible hoses are added in order to compensate the movement of the blade, flapping and feathering [5,6].

The most important advantage of the tip-jet helicopters, compared to the conventional ones, is the omission of the transmission and tail rotor to make a much simpler and cheaper construction, Fig. 2. It leads to a significant decrease in weight of the helicopter and higher allowed payload. Conventional helicopter rotors are driven with the turbo-shaft engine which drives both the main rotor and the tail rotor. The tail rotor is needed to compensate

* Corresponding author.
*E-mail address:* nkolarevic@mas.bg.ac.rs (N. Kolarević).

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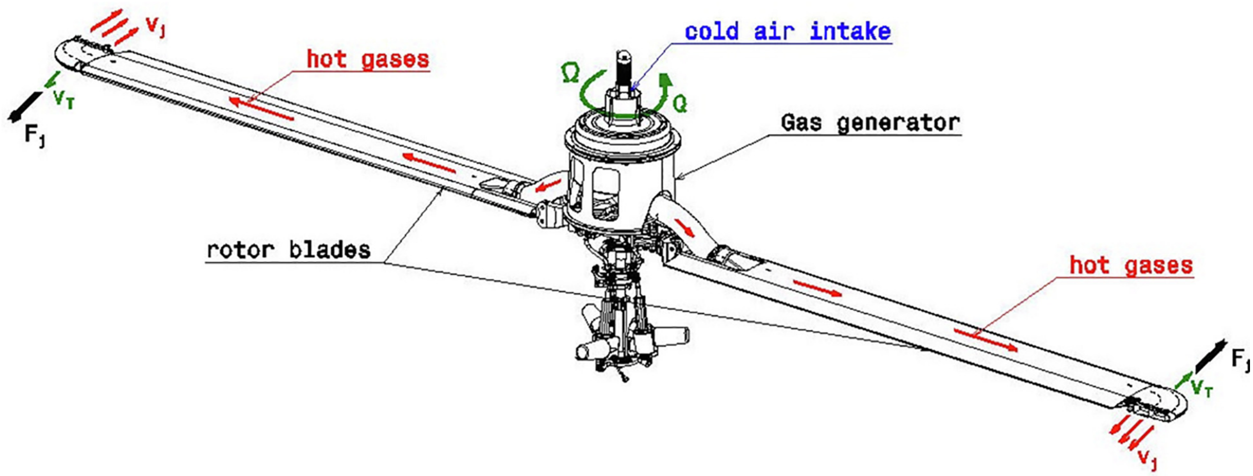


**Fig. 1.** The turbine-compressor subassembly.

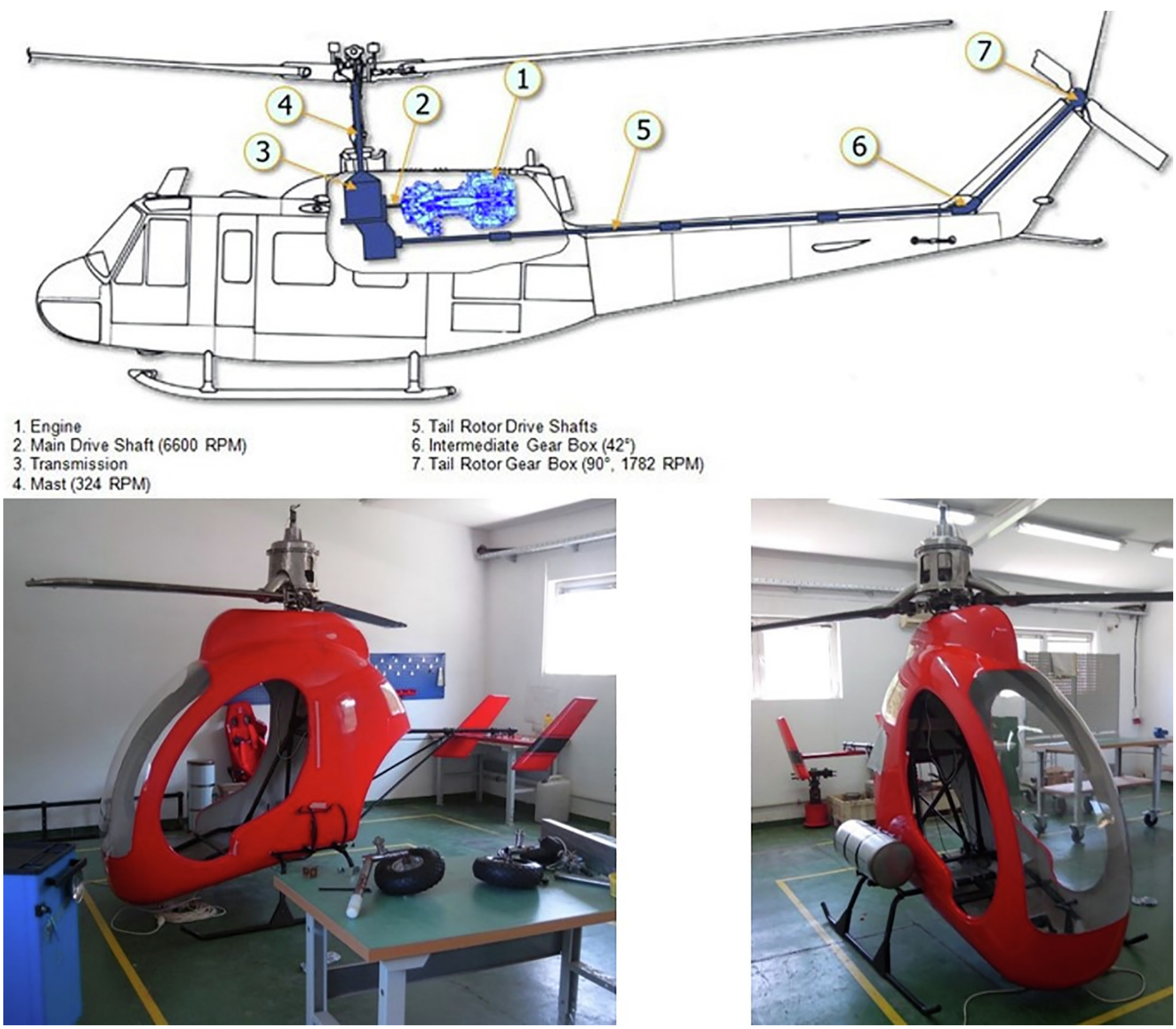


**Fig. 2.** Conventional helicopter above [7] and ATRO-X tip-jet helicopter below.

the reactive moment which is a consequence of the power delivery to the main rotor and tends to rotate the helicopter in the horizontal plane. The entire transmission consists of an engine, several high-speed gearboxes, clutches, transmission shafts, oil systems with tanks etc. Our concept of tip-jet has no transmission and tail rotor. There are only aerodynamic surfaces installed on the tail in order to control the helicopter in the horizontal plane. This makes it a much lighter, simpler and cheaper construction with significantly larger payload. The main drawback of this concept is a significantly lower efficiency, which means more fuel for same time of flight. This fuel weight reduces the previously increased payload capability.

The thrust force that drives the entire propulsion system first of all depends on the available gas generator energy, as well as on pressure losses of the high speed and high temperature compressible flow of the turbine exhaust gas products through the special channel system inside the tip-jet propulsion system. This force governs the performance of the whole tip-jet propulsion system and helicopter. To optimize the performance of the propulsion system and to increase it, a compromise should be made, in terms of minimizing the pressure drop along the pipeline distribution section. By reducing it to an acceptable value, the mass and dimensions should be kept to a reasonable limit. This paper presents the research and the methodology for an estimation of the propulsion force and pressure losses in order to determine the performance of the tip-jet propulsion system as a performance of the helicopter itself. For this case an analytic and 3D numerical mathematical models were made. With a series of tests, the results obtained were compared with the numerical model and verified. The experimental tests were carried out in the EDePro laboratory facilities.

## 2. The propulsion force

The power of the tip-jet system [1] is equal to the product of the torque $Q$ [Nm], angular velocity $\Omega$ [1/s] and efficiency $\eta_{\mathrm{ps}}$.

$$P = Q \cdot \Omega \cdot \eta_{ps}\ [W]$$

The torque is proportional to the thrust forces generated at the blade tips and rotor diameter. For helicopters with two blades the torque is equal to:

$$Q = F_j \cdot D\ [Nm]$$

where $F_j$ [N] is the thrust force at the blade tip, $D$ [m] is the diameter of the helicopter rotor.

The efficiency of the propulsion system can be approximated with the following equation

$$\eta_p = \frac{2v_t}{v_t + v_j}$$

where $v_t$ [m/s] is the absolute velocity of the tip of the blade, tangential velocity due to blade rotation, and $v_j$ [m/s] is the relative velocity of the ejected operating fluid through the nozzle, Fig. 3.

The efficiency is the main drawback of this system and its low value is a consequence of the reduction of the thrust force at the blade nozzle due to its rotation in the opposite direction. So the relative velocity practically produces torque. The desired design point is the one with the ratio of gasses speed to tip speed around 2, which gives as a theoretical maximum value of system efficiency of only 0.67.

Based on this, the main parameter which defines the available power of the tip-jet propulsion system is the effective thrust force, which is the absolute thrust force reduced for the influence of nozzle rotation over vertical helicopter rotor axis. The equivalent nozzle for the gas-generator consists of the distributor of gas-generator that splits the flow into two branches, flexi hoses, blades (their inner channels) and the nozzles on the blade tips. The geometry of this nozzle defines the pressure losses which directly influence the effective thrust force and thus the performance of the entire system. Hence, the entire system of channels must be carefully designed in order to achieve optimal conditions for maximum propulsion force available. If there are high pressure losses due to geometry change and friction, there is a flow that corresponds to small nozzle cross-section area and apart from that it does not lead to enough jet force and it can also lead to engine surging.

It is important to emphasize the phenomenon of the operating fluid compression along the blade, due to the centrifugal force. In a cold cycle, this effect overpowers the hydraulic losses along the blade while in a hot cycle it only decreases pressure losses.

The determining of channel geometry and behavior prediction of the flow through the entire propulsion system is in the first place done with 1D analytical analysis, then with CFD numerical analysis and afterwards verified by ground tests (which include no rotation of the system), tower test (includes the rotation) and flight test – helicopter hovering in real condition.

## 3. Analytical prediction

The tip jet helicopter design requires careful approach when it comes to hydraulic losses inside a distribution system. Total pressure losses are closely related to fluid velocity – they are a function of velocity square $v^2$. The entire propulsion system must be optimized in order to not only gain more power, but also to prevent engine surge and secure stable operating range of a compressor in the first place. To achieve that, fluid velocity inside the distribution channel must be as low as possible. It can be obtained in two ways – using bigger channel surface flow area, or lower gas temperature. Both options have their disadvantages: bigger flow surface area implies a longer blade chord, and lower gas temperature leads to a less power obtained at the main rotor.

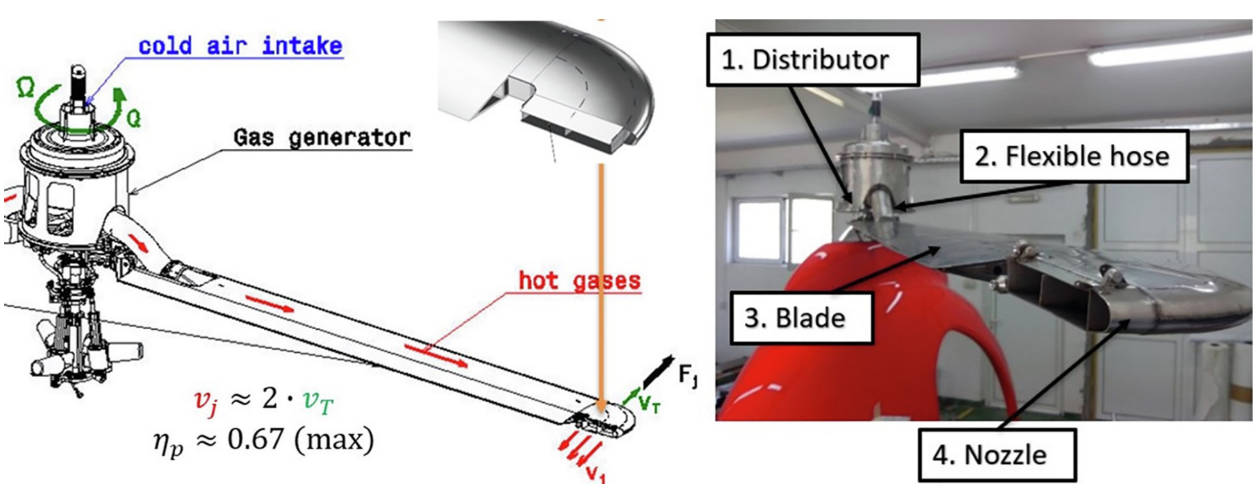


**Fig. 3.** Propulsion force and the nozzle at the blade tip.

In order to achieve optimal design, Darcy–Weisbach equations have been used, and both, frictional and local hydraulic losses took a part in the overall loss of the propulsion system.

$$\Delta p_f = f_D \frac{L}{D_H} \rho \frac{v^2}{2}$$

$$\Delta p_{lhl} = \zeta \rho \frac{v^2}{2}$$

$$\Delta p = \sum_i^n \left(\Delta p_{f,i} + \Delta p_{lhl,i}\right)$$

where $f_D$ is a friction factor defined by a Colebrook equation using iterative procedure:

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\delta/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

Walls are treated as a rough, where $\delta = 0.03$ [mm] is average roughness of the walls.

The Reynlods number, as the ratio of inertial and viscous forces, is defined using Sutherland formula for dynamic viscosity.

$$Re = \frac{\rho v D_h}{\mu}$$

$$\mu = \mu_0 \left(\frac{T_0 + C}{T + C}\right)\left(\frac{T}{T_0}\right)^{3/2}$$

where $T_0$ is a reference temperature, $\mu_0$ is a reference viscosity at the reference temperature and C is a Sutherland constant for a given gaseous material.

It this case, flow must be treated as highly compressible and density change along the gas path must be taken into account. This was achieved using isentropic flow equations and an equation of a state.

$$\frac{p}{p_t} = \left(1 + \frac{\kappa - 1}{2} {M_a}^2\right)^{-\frac{\kappa}{\kappa-1}}, \quad \frac{\rho}{\rho_t} = \left(1 + \frac{\kappa - 1}{2} {M_a}^2\right)^{-\frac{1}{\kappa-1}}$$

$$\frac{T}{T_t} = \left(1 + \frac{\kappa - 1}{2} {M_a}^2\right)^{-1}, \quad \frac{p}{\rho} = RT$$

Static density change has been calculated for a number of stations along the gas path (Fig. 4) using finite length element d$L$ in order to get more precise velocities, and thus total pressure drop. Results obtained this way showed very small discrepancies compared to total pressure losses gained with a CFD analysis.

## 4. Numerical calculation

This type of tip-jet helicopter uses exhaust hot gases from the gas generator exit as the operating fluid. It means that temperature is high and total pressure is low, below 2 [bar]. The combination of these two parameters leads to high speeds obtained in the main rotor blade channel and thus, high total pressure losses. In order to verify results from 1D analysis, CFD has been used.

CFD analysis was performed as steady state analysis using k-ω SST turbulence model that combines best of the k-ω and k-ε turbulence models. Total pressure and total temperature have been used as inlet boundary conditions, and static pressure for outlet boundary condition. Dynamic viscosity is defined using Sutherlands formula, and fluid is approximated as an ideal gas. The analysis was treated as adiabatic, with a high resolution advection scheme. Walls have been defined as rough walls with $\delta = 0.03$ [mm]. In this case there is no rotation of the main rotor, so the effect of additional centrifugal compression inside the blade channel is neglected and the force obtained at the end of the blade must be treated as static force, enlarged for the non-existence of the rotor tip speed $V_0$.

In Fig. 5, the domain for CFD analysis and total pressure distribution along the blade's channel are given. It is obvious that friction, combined with high speed fluid, are the main causes for total pressure loss inside a blade channel.

In order to verify 1D analysis, a comparison of the results from 1D and CFD analyses must be done. Thus, Table 1 presents results from both analyses in every control plane along the blade channel defined in Fig. 4. It is obvious that discrepancies in total pressure loss are small for every control section of the main rotor blade channel.

## 5. Experimental verifications

The verification of mathematical models is done with several tests. First, the entire propulsion system is tested on the ground without rotation. These static tests are used to determine the flow parameters through the channel system and absolute thrust force at the blade end. The first tests are conducted with simple pipes with the same hydraulic diameters as the inner channels which are a rectangular type. We called them fake blades. This test is important because we can easily define the ideal equivalent nozzle, i.e. channel system of the propulsion block. With these tests, by applying the pipes with different diameters, optimal cross-sections can be easily determined in order to achieve maximum static thrust force [1]. Flexi hoses are also installed in order to have the real state of the flow. Then these results are confirmed on the special designed tower test stand for dynamic testing, where the blade rotates. At the end, this propulsion system is installed on

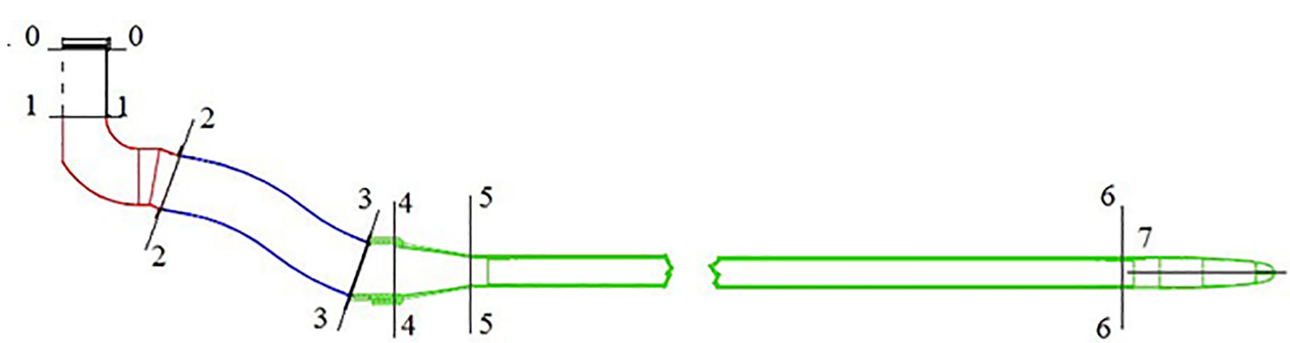


**Fig. 4.** Control station along a blade channel.

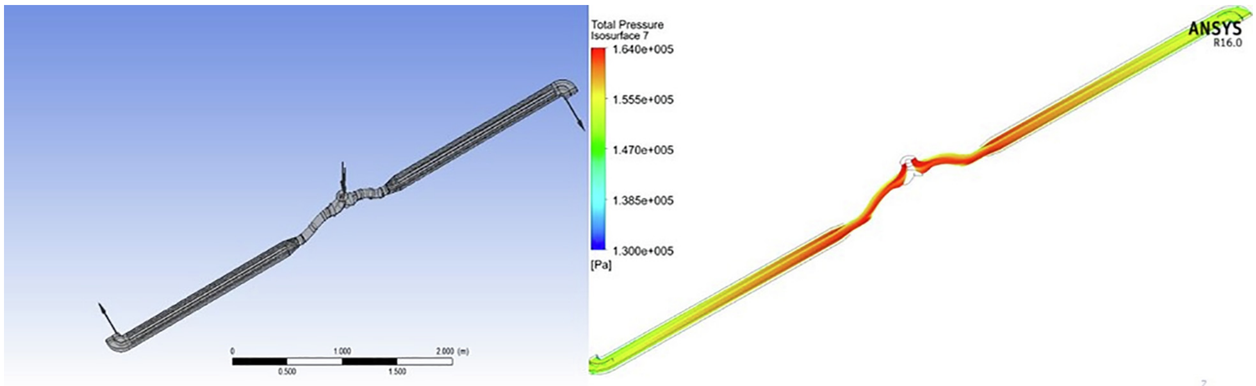


**Fig. 5.** CFD Domain and total pressure distribution along a blade channel.

**Table 1**
Comparison of 1D and CFD results.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Control plane | 0-0 | | 1-1 | | 2-2 | | 3-3 | |
| Analysis | 1D | CFD | 1D | CFD | 1D | CFD | 1D | CFD |
| $p_t$[bar] | 1.64 | 1.64 | 1.639 | 1.639 | 1.616 | 1.619 | 1.597 | 1.603 |
| Control plane | 4-4 | | 5-5 | | 6-6 | | 7-7 | |
| Analysis | 1D | CFD | 1D | CFD | 1D | CFD | 1D | CFD |
| $p_t$[bar] | 1.565 | 1.599 | 1.563 | 1.593 | 1.565 | 1.599 | 1.563 | 1.593 |

the helicopter fuselage, and with hovering tests complete matching of the results was achieved, compared to the tower tests.

In order to determine the behavior and the state of the gas generator, several sensors are installed onto the acquisition system [8]. This part of the acquisition system determines the inlet parameters of the tip-jet propulsion system, the parameters of the operating fluid which enters the gas generator distributor. In order to measure the flow parameters through the inner channels of the propulsion system, during static tests, two pressure transducers and one thermocouple temperature sensor are added, Fig. 6. One pressure transducer is placed on the gas generator distributor and measures the inlet total pressure of the operating fluid. The other pressure transducer is placed on the blade nozzle and it measures the outlet total pressure of the propulsion system. The difference between these two values of pressures defines the total pressure drop through the channel system. These probes are provided with the special curved pipe, placed in such way that its orifice faces directly in the flow in order to measure the total pressure. The remaining overpressure is used to generate the thrust force by accelerating the flow in the nozzles, which leads to the fact that pressure drop directly influences the amount of the thrust force. Thermocouple is used in order to monitor the outlet temperature of the operating fluid which gives the information of the maximum available energy that can be used from burning the fuel. Load cell is installed on the level system in order to measure the forces and torque.

OMEGA PX602-150GV pressure sensors have been used, with the following characteristic: accuracy 1%, maximum pressure 300 psi, span 150 psi, input voltage 5–10 Vdc, output signal 10 mV/V, etc. The combustion products temperature is 650 °C, with the limit value of 700 °C. Due to the high temperature, the combustion product mixture had to be cooled down to an appropriate level so that the pressure sensor will not be damaged. The copper pipes are installed between the sensor and the measuring point. The copper wire was enough to reduce the temperature during the few minutes of experiment running, but such system demands additional calibration. For this purpose, we use the compressor installation with the heating chamber, which constantly provides the flow of exact temperature and pressure. A solution similar to this has been applied for monitoring and measuring

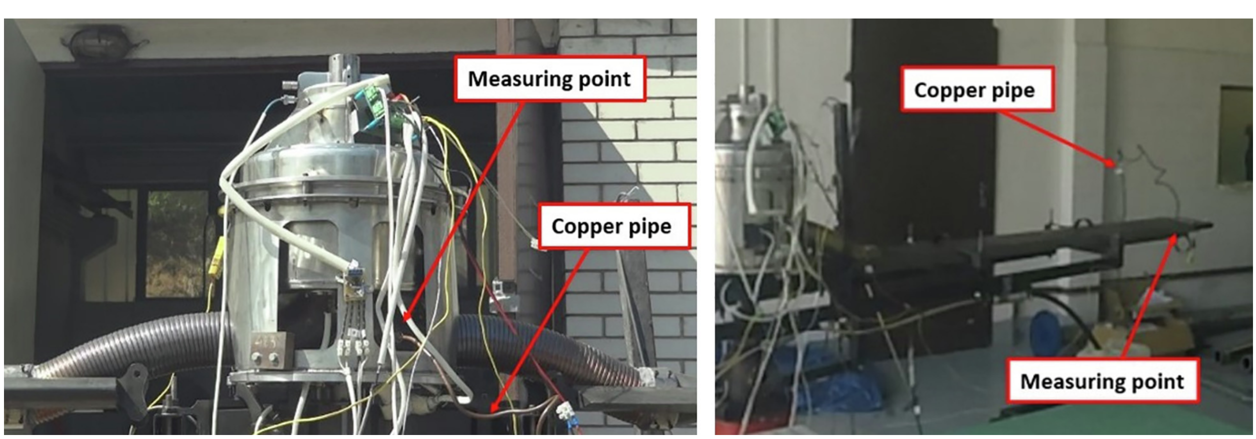


**Fig. 6.** Acquisition system.

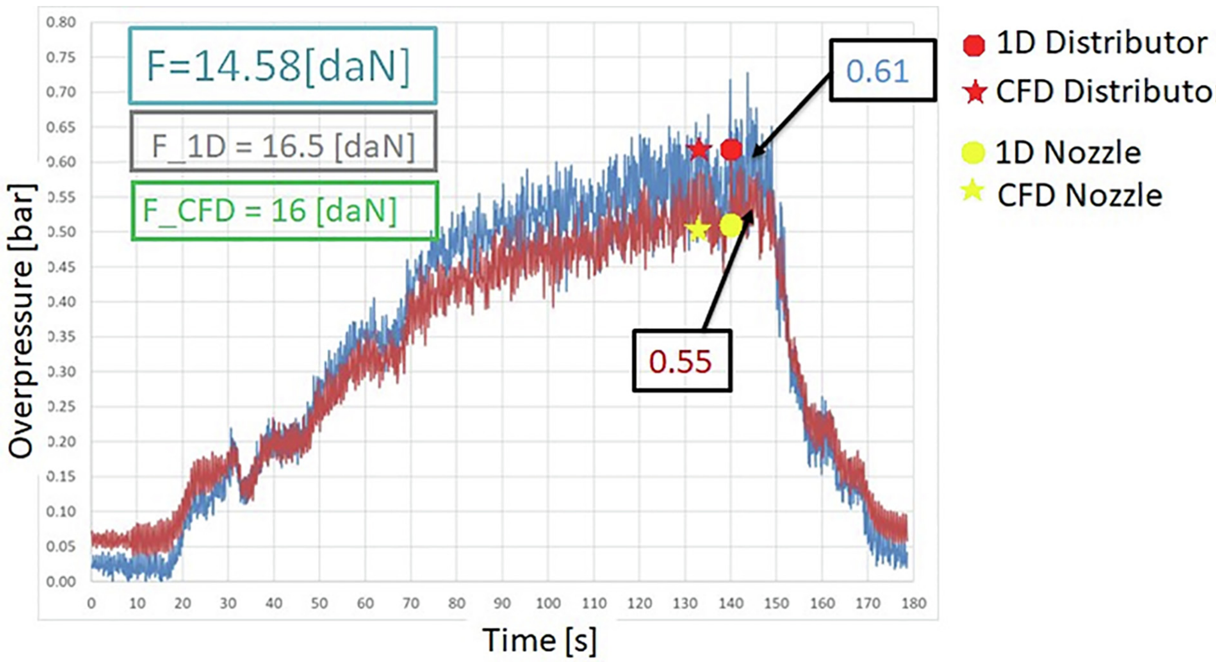


**Fig. 7.** The comparison of the CFD, 1D and experimentally measured pressure and force values.

the pressure on the gas generator nozzle, which is additionally explained in paper [9].

The result of the measured pressure and force values and force values obtained by analytical 1D and numerical 3D models on the gas generator operating regime at 58,000 rpm are presented in the diagram in Fig. 7. It can be concluded that the analytical model gives quite satisfying values for the thrust force of some preliminary design of tip-jet propulsion systems. But, the difference between force values obtained by mathematical calculations and experimentally measured force value of 14.58 daN is mostly a consequence of the operating fluid leakage in flexi hoses, and its high roughness. These hoses were not completely sealed, especially on points of high deflection. This leakage was reflected in the decrease of mass flow together with the pressure and the force at the blade nozzle. In addition to this, in tests without flexi hoses and with fake blades (circular cross-section and low roughness), we managed to achieve the trust force of 18.75 daN.

## 6. Conclusion

The experiment and numerical simulations show that there is a significant pressure drop through the channel system inside the tip-jet propulsion system. Efficiency can be increased by elongating the blades, i.e. with an increase in the rotor diameter, which causes higher pressure losses but the force arm is bigger, so the torque is larger. This is the reason why tip-jet helicopters have the larger rotor diameter compared to the conventional helicopters.

The results obtained from the CFD analysis and experiments showed that discrepancies between 1D model, on the one hand, and experimental and CFD on the other hand, are very small, and 1D model can be used as a quality tool for a fast and reliable dimensioning of the tip-jet helicopter gas distribution system.

At the end, we manage to successfully lift the helicopter of 240 kg, and these hovering tests proved that the tip-jet propulsion system can be used as an independent propulsion block on different helicopter constructions.

## CRediT authorship contribution statement

**Nenad Kolarević:** Methodology, Writing - original draft. **Stevan Crnojević:** Investigation. **Miloš Stanković:** Writing - review & editing, Visualization. **Nenad Latković:** Methodology, Formal analysis. **Marko Miloš:** Validation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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