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(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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Evaluation of the performance of an axial one-stage 10kW turbogenerator through experimental testing

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ABSTRACT

The paper describes the results of experimental research on a prototype one-stage turbo-generator with a nominal power of 10 kW and a rotational speed of 24 000 rpm. The expander at the Institute of Fluid-Flow Machinery, Polish Academy of Sciences was developed as part of the R&D project with Marani company. The unit construction consists of an overhanging rotor and shaft mounted on rolling bearings. The turbo-generator was tested on a specially constructed laboratory test stand in the first stage. Compressed air instead of refrigerant gas (R1233zd) was used. The test results converged with the parameters obtained using the RANS simulation. The convergence for the turbine mass flow was 97% of the value obtained in the CFD model, which is satisfactory. The power generated by the turbo-generator, which was compared at this stage, also achieved satisfactory convergence (95% to 97%) with the calculation model. These tests allowed determine the compliance of the adopted design assumptions and confirmed the correctness of the calculation tools used.
The next stage of work was to examine the ORC unit in operating conditions. That stage was aimed at checking the correct work of the machine with the ORC system. The turbine achieved internal efficiency calculated from temperatures at a level slightly lower than that obtained from numerical calculations (total-to-static efficiency). The efficiency was equal to about 73%, and the difference between calculated and measured values do not exceed 0.25 pp. (percentage point). The electric efficiency was about 65% and a maximum electric power output of 6.8 kW was measured.

1 INTRODUCTION

The rise in energy consumption over the past century has led to increased emissions of greenhouse gases, subsequently resulting in a rise in global temperatures. Continuing on this trajectory could yield detrimental effects, such as escalating destructive weather phenomena (Ramanathan and Feng, 2009). The industry sector was one of the first to enact climate regulations, with various sectors having unique methods for reducing CO2 emissions. Particularly in steel and aluminium production, waste heat recovery presents an ideal opportunity to boost overall process efficiency.

The Organic Rankine Cycle (ORC) technology has emerged as a promising solution to facilitate energy recovery from waste heat within the industry. ORC systems are specifically engineered to synergize with industrial apparatuses such as compressors, large engines, or various eco-friendly technologies. The fundamental components of ORC systems include a turbine, pump, condenser, and evaporator. These systems operate based on the Organic Rankine Cycle. The fluids utilized in this context differ from water and include, for instance, hydrocarbons and refrigerants. The fluid selection process was thoroughly described by (Klimaszewski *et al.*, 2019).

ORC turbine design offers a fertile ground for optimization. The rotor and stator geometry can be numerically analyzed using specialized software. Various publications address this issue. (Witanowski

et al., 2023) presented the Nelder-Mead optimization of a single-stage axial turbine in their paper. The turbine, functioning within the ORC system, utilized R7100 as the working fluid. The optimization results were promising, with the total-to-static efficiency of the new geometry increasing by about 5.5 percentage points at the design point.
An alternate approach involves optimizing the ORC turbine to operate in two distinct work modes: for parameters appearing in cogeneration and condensation mode. A multi-objective optimization for a turbine working with MM was conducted by (Witanowski *et al.*, 2023). The authors identified a flow path with improved efficiency using the Implicit Filtering algorithm. A substantial efficiency increase of 4.8 percentage points was observed in the cogeneration mode, and in the cogeneration mode turbine efficiency, it increased by about 3.1 percentage points. Another significant approach in the optimization field involves hybrid algorithms, as the blade shape optimization geometry discussed (Witanowski *et al.*, 2023).

Authors of various publications have conducted experimental tests on ORC turbines, either on a test stand or as part of an ORC system. Kang, S. H. (Kang, 2016) describes preliminary tests of an ORC turbine coupled with an ORC system. The working fluid was R245fa. A two-stage radial expander was used, with the generator directly connected to the turbine. The installation achieved a maximum electric power of 39 kW, a cycle efficiency of 9.8%, and turbine efficiency based on output equal to 58.4%. The author highlighted the potential for further efficiency improvements via the reduction of heat and pressure losses.

The article (Fu *et al.*, 2015) details an ORC system designed for an electric power output of 250 kW. The preliminary test results were quite satisfactory. The system achieved a maximum net power output of approximately 219.5 kW, a maximum thermal efficiency of 7.94%, and a turbine speed of 12,386 RPM, with an isentropic efficiency equal to 63.7%. The working fluid used was the refrigerant R245fa. The power generated by the turbine was transferred to the generator via a gearbox, with the electric generator maintaining a rotational speed of 3600 RPM.

The authors of the publication (Borsukiewicz-Gozdur, 2013) outlines experimental research conducted on an ORC power plant. The ORC installation was designed to operate with a geothermal heat source, with hot water temperatures ranging from 66ºC to 111ºC. The experiment also involved a hermetic turbine working with R227ea fluid as part of the ORC system. The turbine generator was designed for a rotational speed of 3000 RPM, a standard value in the power grid. The electric efficiency of the ORC system was approximately 4.88%.

2 TEST STAND

The test stand was built in the laboratory of the Institute of Fluid Flow Machinery Polish Academy of Sciences. The turbine (no. 2 in Figure 1) was mounted on the test stand. The test stand consists of a compressor connected with an air heater and flow meter (no. 1 in Figure 1), a system of valves for fluid control connected by pipelines (no. 4 in Figure 1), a generator cooling system (no. 5 in Figure 1). The measuring system includes pressure sensors and thermocouples (no. 6 in Figure 1) that elements are connected to a device for data collection. The mobile measurement instruments were used to control the machine's mechanical vibrations and the shaft's displacement.

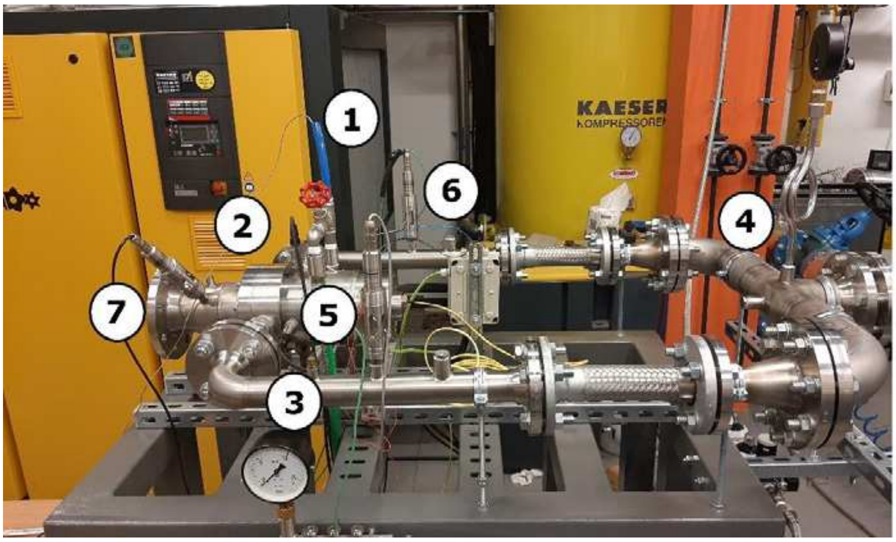

Figure 1 Turbine 10 kW on a test stand, 1-compressor, 2-turbine, 3- feed pipeline, 4 - control valves, 5 – cooling system, 6 – pressure transmitter, 7- turbine outlet.

The ORC turbine was designed to work with R1233zd, a refrigerant with low global warming and ozone deployment potential. The 10 kW turbine investigation on the test stand was carried out with substitute medium - air. The main reason for using air instead of R1233zd on the laboratory test stand was the complexity of building a system for testing with refrigerant. At this stage, the primary goal was to test the mechanical construction, specifically the vibration level in the x-axis. The test stand allows also to check of the mechanical working parameters of the turbine and check the quality of fabrication flow system elements.

The installation works as follows: compressed air goes by pipelines from the compressor to the heater, and hot air is divided into two streams for the left and right inlets on a turbine. The outlet is open, the air goes to atmospheric conditions. The pipeline delivering fluid to the turbine was marked as no. 3 in Figure 1, the turbine outlet was shown as no. 7 in Figure 1. The fluid flow throw machine was controlled, the parameters like temperature, pressure and mass flow were measured and analysed. The laboratory installation includes the main cycle five pressure and five temperature sensors.
The test stand also includes a separate cooling water system used for generator cooling (more details were described in the article (Zaniewski *et al*., 2023)).
The power system consists of a water resistor and an electro-energetic converter for controlling electric power parameters.

3 10 KW TURBO-GENERATOR TESTS

Tests in the laboratory consist of three phases. The first phase include a direct load of the turbogenerator, the water resistor was directly connected to the turbine generator, and the electric load was controlled by the mechanical movement of elements. When the parameters of the research were satisfied then, the next phase include the use electro-energetic device. The device connects the turbogenerator with the electric grid indirectly, allow also to control its work parameters. In the second phase electronic device was used to connect indirectly with a water resistor. In the third phase, the connection was prepared to an electro-energetic grid.
The observed parameters were static pressure on an inlet, total temperature on the inlet, the total temperature on the outlet, mass flow, rotation speed and electric power.
In that part of the investigation, parallel conduct tests of vibrations parameters were conducted (Figure 2). Necessary to define the quality of the mechanical work of a machine. All tests were achieve satisfied values and did not exceed recommend values for that kind of micro-turbines. The recommended values

are based on the standard ISO 20816 (Industrial machinery with a power rating above 15 kW and operating speeds between 120 r/min and 30 000 r/min).

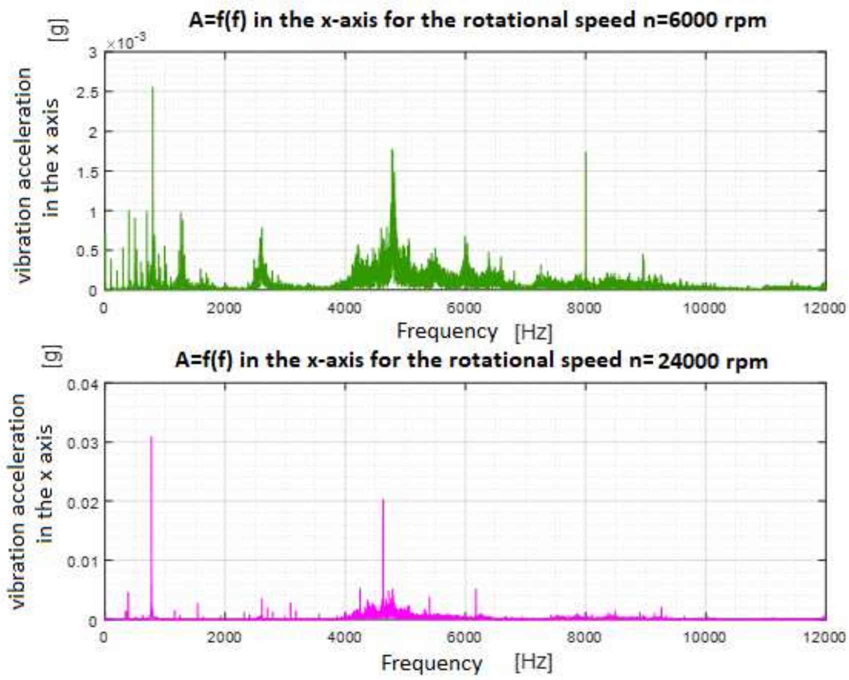

Figure 2 The amplitudes of vibration acceleration in the Y axis for the frequency spectrum up to 12000 Hz recorded for the speed of 6000 rpm (upper graph) and the nominal speed of 24000 rpm (lower graph) respectively.

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The amplitudes of vibration acceleration in the X axis for the rotational speed of 6000 rpm and 24000 rpm are shown. The peak values achieved at nominal speed are an order of magnitude higher than at much lower rotational speeds.

4 CFD RESULTS ANALYSIS COMPARED TO EXPERIMENTAL RESULTS

The CFD calculations were used to verify experimental results. The mathematical model was solved with the use of CFD methods. Numerical methods include the body's inlet domain and the diffuser's outlet domain. The addictive losses connected with bearing and windage were also included.
The mash was present in Figure 3. The computational mesh was prepared with Ansys Turbogrid and ICEM software. The mesh domain includes a rotor and stator consisting of 26 629 378 elements and 28 430 740 nodes, the mesh is hexahedral. The area with more density mesh includes the rotor and stator, that area was the most important for calculations of fluid flow and boundary layers. The stator mesh domain includes 4 644 640 nodes and 4 227 440 elements. The rotor domain includes 10 850 840 nodes and 10 107 860 elements.

The Ansys CFX code uses the RANS equations with the k-ω SST turbulence model to describe fluid dynamics. The finite volume method with a second-order discretization scheme is used to solve these equations. The inlet boundary conditions include total pressure, total temperature, and flow direction. The outlet boundary condition is the average static pressure. The frozen rotor technique, also known as the multiple reference frame method, is used to handle the stationary stator domain and the moving rotor domain.

The total pressure on the inlet domain used for calculation was equal to 1.82 bar and the total temperature was set at 45.3°C, the turbulence was on the medium intensity (5%). The analysis performed in this study was stationary, with a constant rotor speed equal to 13,700 rpm. The experimental and simulation results were compared and it was assumed that the fluid used in the simulation was air, modelled as an ideal gas. On the outlet domain, relative pressure was equal to 1.027 bar and the pressure profile blend was set as 0.05.

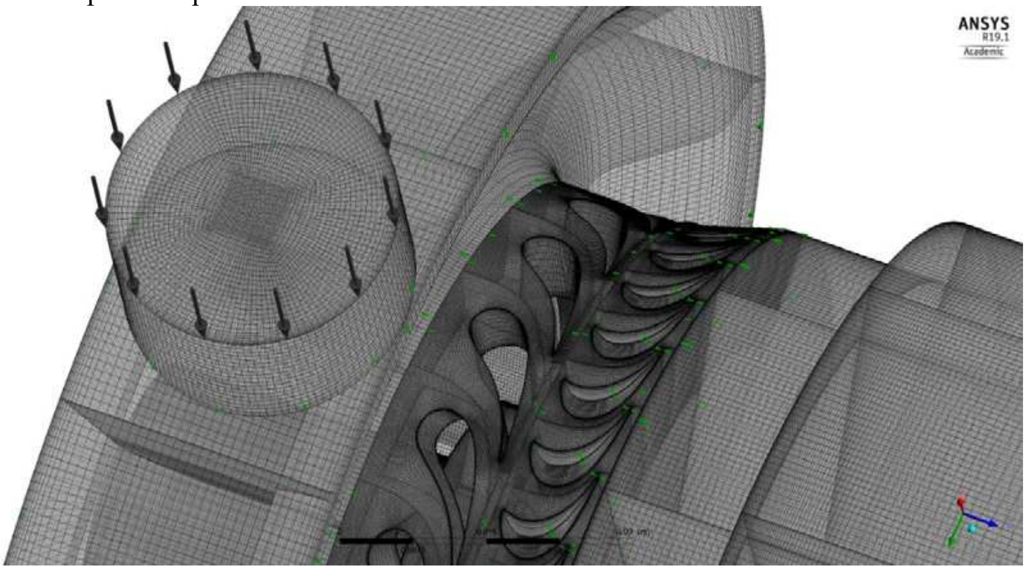

Figure 3: Computation mesh, visible an area with high density

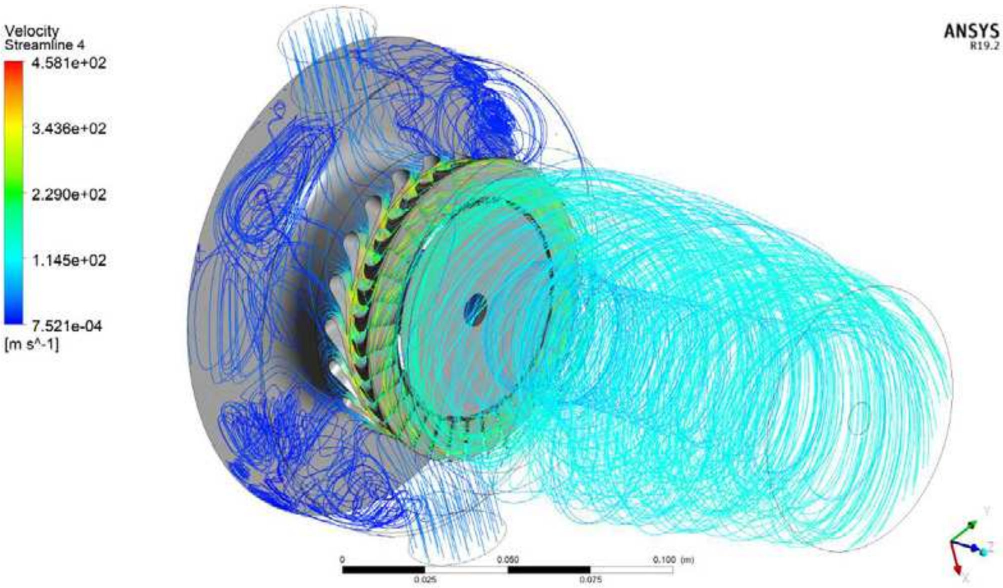

Figure 4: Streamlines for nominal works parameters.

The streamlines were presented in Figure 4. The area with higher velocity is marked by red colour. The lower speed is shown by blue colour. The flow throws the rotor and stator correctly and in line with the assumptions. The highest speed was observed at the stator outlet. The streamlined figure on the impeller area does not appear incorrect phenomenon. That means the flow system was correctly designed.
The pre-processing was conducted with the use of Ansys CFX pre-processor, and numerical calculations were conducted with the use of Ansys CFX solver.

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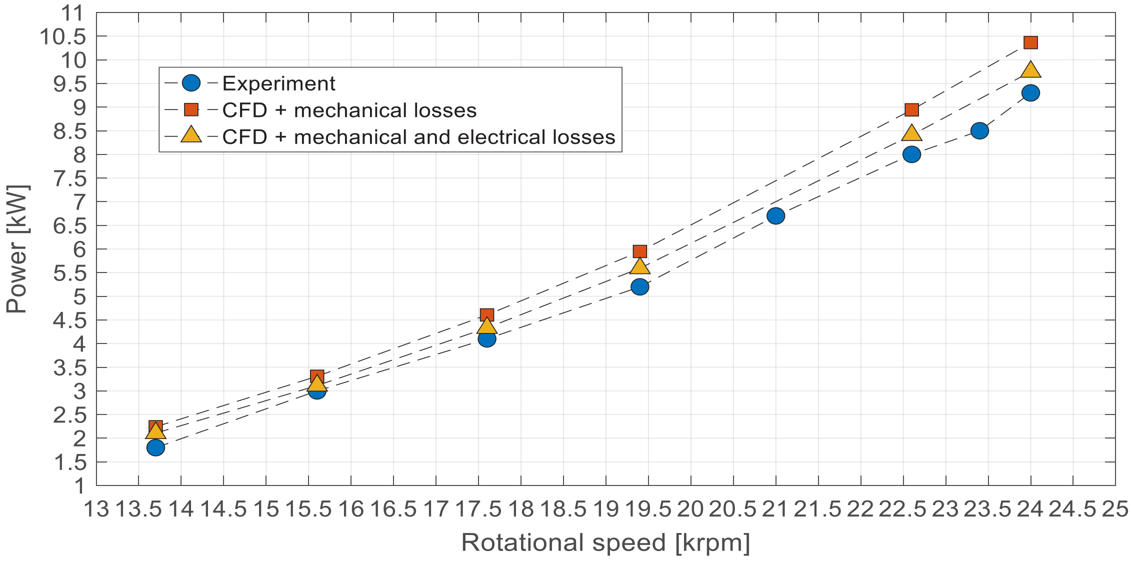

Figure 5 Electric power achieve in the experiment in the function of rotational speed comparison to functions of rotation speed for choosing numerical models.

The results of numerical calculations and experimental data were presented in Figure 5. The convergence for nominal parameters was on the satisfied level, for low values of rotation speed was equal to 97% for high 95%. The electrical efficiency of the generator was equal to 94%. The electrical efficiency value was determined based on the information provided in the technical documentation of the electric generator and energy conversion system. This value also takes into account the losses that result from the experience of the Institute of Fluid Flow Machinery team. By considering both the documented specifications and the team's expertise, a comprehensive assessment of the electrical efficiency was achieved. The red points describe the results of the experiment, the blue points show the results of CFD calculation considering losses in bearings and friction losses values, and the orange points includes also electrical losses. The achieved values of CFD calculations include the domain of the full stator domain and rotor domain.

5 THE RESULTS OF TURBINE TESTS ON THE ORC UNIT SYSTEM

The next stage of tests was a laboratory test of the ORC unit with conditions similar to industrial. The turbine was mounted in the ORC installation, the pipelines of the inlet and outlet were connected, and the measured devices were calibrated. The tests of the turbine were conducted on the designed, working fluid R1233zd. The tests of ORC installation were conducted in the laboratory in controlled conditions. The heat was assured by the heating system based on the gas boiler. The main object of the experiment was the turbine (Figure 6 no.1). The control of the cycle parameters was assured by the pump (Figure 6 no.2), flow meter (Figure 6 no.5), control valve (Figure 6 no.4) and heat exchanger (Figure 6 no.3). The level of vibration does not exceed safety values. Measured parameters of fluid flow in the different points of the fluid system confirmed the correction of calculation. The construction was hermetic, there are no appear leakages or other unexpected damages.

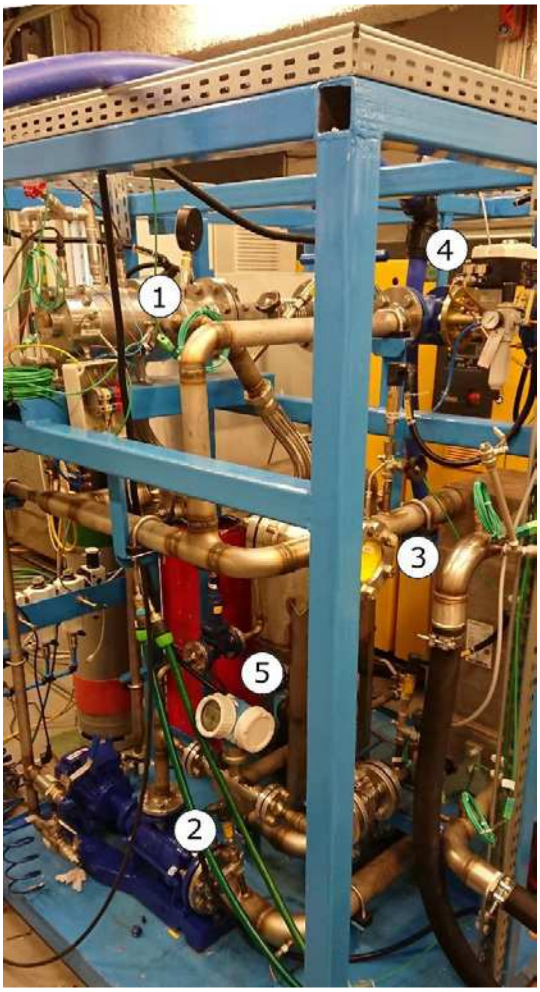

Figure 6 Turbine installed on ORC plant, 1 – turbine, 2 – feed pump, 3 – heat exchanger, 4 – control valves, 5 – flow meter.

The third stage of tests was conducted in industrial conditions. The ORC system was connected to an air compressor, and the hot compress air was a source of waste heat. The data for parameter calculation were collected based on the sensor system. Sensors, similar to the preview stage of the experiment measured different parameters on the ORC loop like temperature, pressure and mass flow. The data from sensors allow for calculating the efficiency of the turbine and ORC cycle. The efficiency was calculated with the use of different parameters, first base on temperature calculation, second base on power generated by water resistor, and third base on power achieve in electro energetic system. The first method get the best results and efficiency was the highest, the value was equal to about 72%. In that method, temperature and pressure values were used to find the enthalpy value for fluid. Then based mass flow was calculated efficiency with the use of Equation (1). The efficiency calculated by the second method achieve a value of about 60%, the third method get the worse results, and the efficiency was about 57%. The changes in efficiency in the function of time was presented in Figure 7.

$$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{1}$$

The efficiency of the ORC cycle was presented in Figure 8. The chart presents a change in the efficiency of the function of time. The ORC cycle efficiency achieves the highest value base on the temperature measurements. A description of the calculation method of cycle efficiency was present in Equation (2). This equation also takes into account the loss parameter, including pump energy consumption, pipe losses, and more. The calculation base on the temperature achieves a value of 6%. The temperature of hot water, the source of heat for ORC installation, was equal to 74°C on the evaporator inlet. The temperature of cooling water, at the condenser inlet was equal to 12°C. The second efficiency taking into account the process of energy conversion and electrical losses achieved a value of about 4.6%.

$$\eta_c = \frac{\dot{m}(h_2 - h_1)}{Q_s} - P_{AX} \tag{2}$$

The peaks visible on the charts result from the unstable work of the heat source. The industrial tests get satisfactory results. The main goals were achieved.

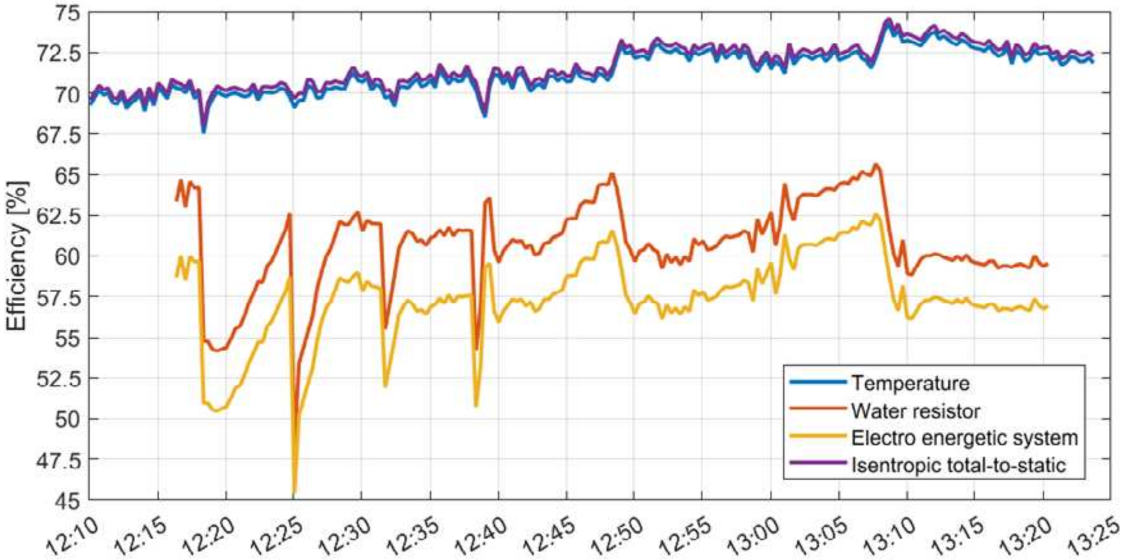

Figure 7 Efficiency of the turbine based on data from different measurement systems.

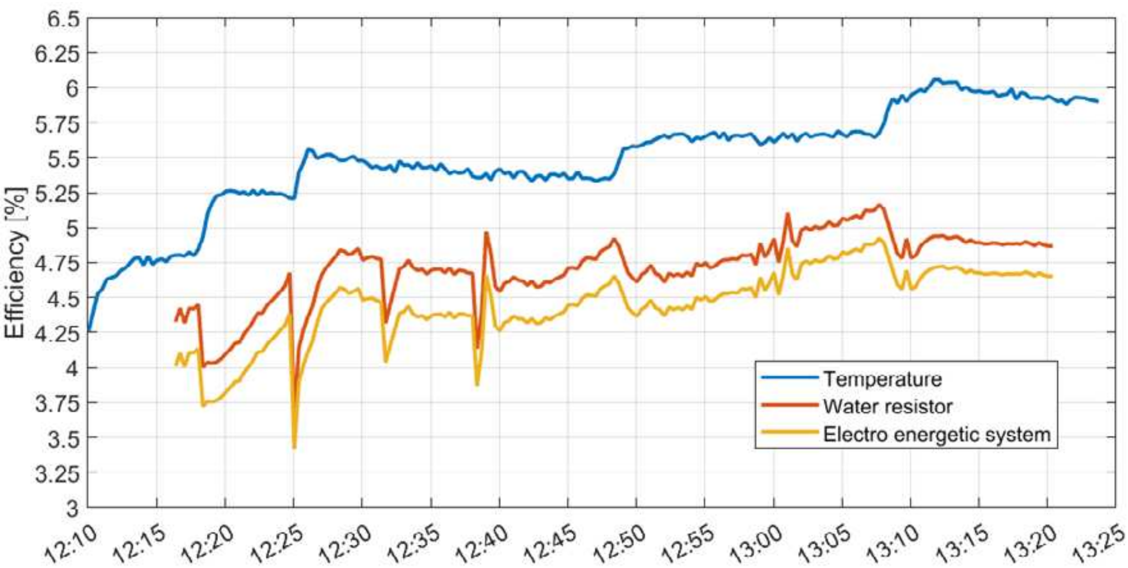

Figure 8 The ORC cycle efficiency base on different source

6 CONCLUSIONS

In this study, a three-phase experimental approach was employed to assess the performance and efficiency of a turbine incorporated into an ORC unit. This procedure involved independent turbine evaluations, laboratory tests, and full-scale industrial testing. The following conclusions summarize the key findings from the investigation.

- The experiment proceeded in three distinct stages. Initially, tests were conducted to disconnect the turbine on a dedicated test stand. Subsequently, laboratory tests were carried out to evaluate the turbine mount integrated with the ORC unit. The final phase encompassed testing the ORC unit within an industrial setting.
- The standalone turbine tests delivered satisfactory results, generating an electric power output of approximately 9 kW and achieving a rotor speed of 24,000 RPM.
- The second phase of testing proved equally successful. The primary focus was on examining the mechanical connections and operating parameters of the turbine when coupled with the ORC system under laboratory conditions. The results aligned with the predictions, with the observed data closely matching the CFD simulation values.
- The ORC unit exhibited satisfactory performance during the industrial testing phase, achieving an efficiency rating of approximately 4.6%.
- Based on the empirical data collected, it is concluded that the machine operates optimally in terms of field flow efficiency.

NOMENCLATURE

h_1	enthalpy on turbine inlet	[kJ/kg]
h_2	enthalpy on turbine outlet	[kJ/kg]
h_{2s}	isentropic enthalpy	[kJ/kg]
$\dot{m}$	mass flow	[kg/s]
P_{AX}	cycle losses	[-]
Q_s	heat source	[kJ/s]
η_c	efficiency of the cycle	[-]
η_t	efficiency of the turbine	[-]

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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