Development of a micro ORC power unit using digital prototyping methods

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Abstract. The development of the prototype of the ORC micro turbine includes already in the design phase the creation of a digital prototype based on the use of computational simulations, especially the CFD flow program Simcenter STAR CCM +, strength and rotor-dynamic FEA analyses of system behaviour - Simcenter 3D. This is followed by the optimization of the device by increasing its efficiency and improving the mechanical properties of the system. For this purpose, we used the optimization program HEEDS and the topological optimization method Simcenter 3D. This was followed by the production of a prototype, where 3D printing technology was used to produce turbine housing moulds and other components. A huge attention of this contribution is devoted to these additive production processes.

1 Introduction

The principle of an ORC power unit is a steam engine cycle where the working fluid is an organic medium that receives heat from an external source into a closed loop. The device converts the thermal energy into mechanical work, which can be used to generate electricity or to drive other equipment (e.g. a refrigeration compressor). The working fluid undergoes phase changes during the cycle. The duty cycle of the Organic Rankine Cycle (ORC)unit is shown in Fig. 1.

Refrigerants are most commonly used as the working medium to allow the use of low potential heat, from any energy source, both from the primary source and waste heat (WHR). Then it is a renewable source with zero emissions and universal use.

The aim of our project is the development of a micro ORC micro combine heat and power (μCHP) unit with a capacity of 1.5 and 5 kW.

1.1 Use of micro ORC units

In the case of micro cogeneration, this is up to 50 kWe. The principle of cogeneration is the production of both thermal and electrical energy from both primary and secondary sources. In the case of primary sources, it will allow us to cover local electricity consumption, reduce transmission losses and allow operation in an independent island system. It is a highly efficient process for using primary energy, with an efficiency of up to 95%.

In the case of waste heat recovery (WHR), it is possible to process residual heat from the flue gases of biomass boilers, process heat from food, wood, glass and chemical plants or conventional combustion engines used to drive compressors or energy centres.

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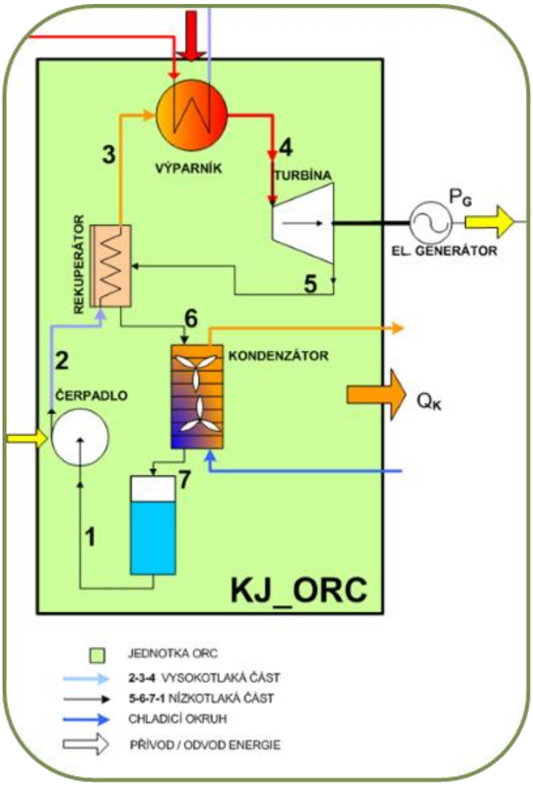

Fig. 1. Demonstration of the ORC cycle principle
1-2: the working medium in liquid state is supplied and compressed from the reservoir by a circulating pump
2-3: in the recuperator the medium is preheated by steam from the turbine outlet
3-4: in the evaporator the medium is further heated, evaporated and superheated (dry steam)
4-5: steam expands in a turbine, which does mechanical work and drives e.g.an electric generator
5-6:in the recuperator, the outlet steam is partially cooled by heat exchange with the liquid medium
6-7:in the condenser, the medium is cooled by the cooling circuit (air, water...) and condense
7-1: condensate is collected in the reservoir and then supplied by pump = the cycle is closed

2 Specifics of the proposed solution

The main criterion of our approach to the design of the µCHP ORC unit was to achieve the highest possible efficiency of the whole plant and low production costs. This is based on the economic viability of these small power plants, where the return on the investment is at the break-even point. Thus, there was a need to design a device that would have high efficiency for power generation and yet be inexpensive.

The main components we focused on were the choice of the expand machine used and the choice of the appropriate working medium.

The aim was to develop a µCHP unit with a capacity of 1.5 and 5 kW. The design and performance parameters of the 1.5 kW unit are shown in Table 1.

Table 1. Input and power parameters of the unit

Parameter	Nominal value	Unit
Inlet pressure	10.4	bar
Inlet temperature	100	°C
Heat output of the source Q_s	21	kW_t
Electrical power at terminals	2,0	kW_e
Net electrical power	1,5	kW_e
Inlet temperature of cooling water	30	°C
Outlet temperature of cooling water	50	°C
Usable heat Q_c	18	kW_t
Total efficiency of the ORC circuit (Q_c/Q_s)	85	%

2.1 Micro turbine

Most attention was paid to the choice and design of the expander. We needed to achieve the highest possible efficiency over the widest possible operating range of temperatures and steam flow rates, and at the same time we needed the most compact dimensions so that the entire ORC unit could be supplied in combination with 25 kW biomass boilers. In the end, we chose a single-stage micro turbine with an axial arrangement, partial admission and action impeller stage.

We designed the micro turbine unit in a unique arrangement subject to a utility model. The unit includes the turbine itself with inlet spiral, partial spray nozzles, impeller with balancing holes and outlet diffuser.

The turbine shaft is connected to the generator or alternator gearbox by an electromagnetic coupling. The electromagnetic coupling contains a baffle which hermetically separates the refrigerant circuit from the surrounding environment and predisposes the entire ORC unit to automatic and maintenance-free operation. The ball bearings are lubricated with refrigerant and no servicing is required. An example of the ORC micro turbine arrangement with gearbox and generator is shown in Fig.2.

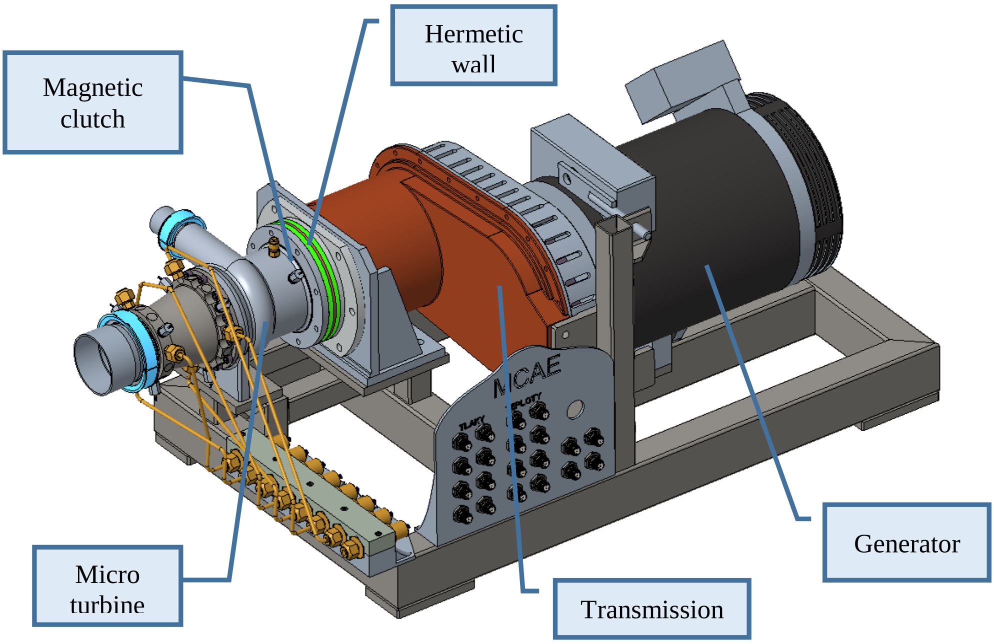

Fig. 2. Example of a 1.5 kW micro turbine with magnetic clutch, gearbox and generator.

2.2 Choosing a suitable refrigerant

The thermodynamic properties of the refrigerant can strongly influence the efficiency of the entire cycle. The thermodynamic efficiency depends on the interaction of thermodynamic properties of the medium such as critical point, specific heat, density, etc. A high vapour density will give us a smaller volume and therefore a smaller device size, a low viscosity means better heat transfer and lower frictional losses, and a lower evaporation pressure will make the device design easier.

Stability at higher temperatures (eliminating degradation) and the safety and toxicity of the medium and flammability are also important properties of the medium. Recently, there has also been a lot of attention paid to the environmental impact of GWP media (Kyoto, Montreal Protocol and Paris Agreements). Last but not least, the availability and cost of the media are equally important. An illustration of the characteristics of different media is shown in Fig. 3 together with the design of the ORC cycle of a μCHP unit in a T-S diagram. For the temperature range we used, we chose the refrigerant R245fa which was eventually replaced by the environmentally friendly version R1233 Zd(E).

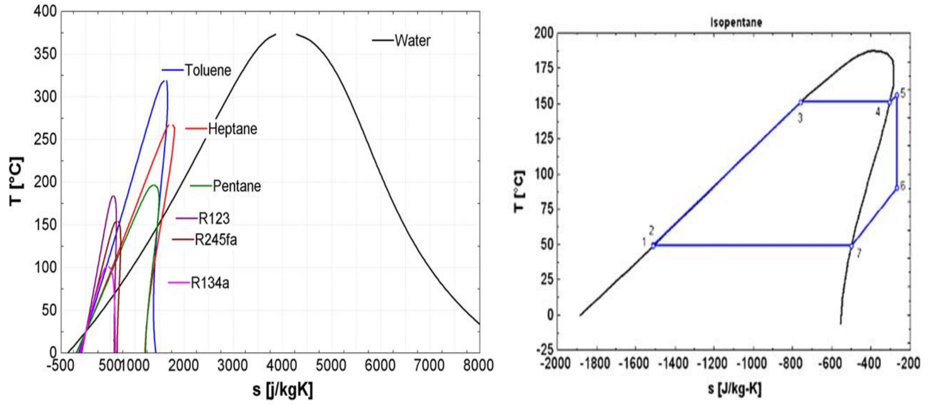

Fig. 3. On the left is an example of the behaviour of different types of refrigerants in a T-S diagram and on the right an example of the designed ORC cycle of a micro CHP unit.

2.3 Description of the µORC unit test circuit

The 1.5kWe µCHP test plant was operated in combination with an 18kWe electric boiler, which supplied 1000°C water to the steam super heater. The steam, which was subsequently processed in the micro turbine, condensed in an air-cooled condenser and from there was again supplied to the steam super heater by a pump via a recuperator.

A schematic of the ORC test circuit is shown in Fig. 4.

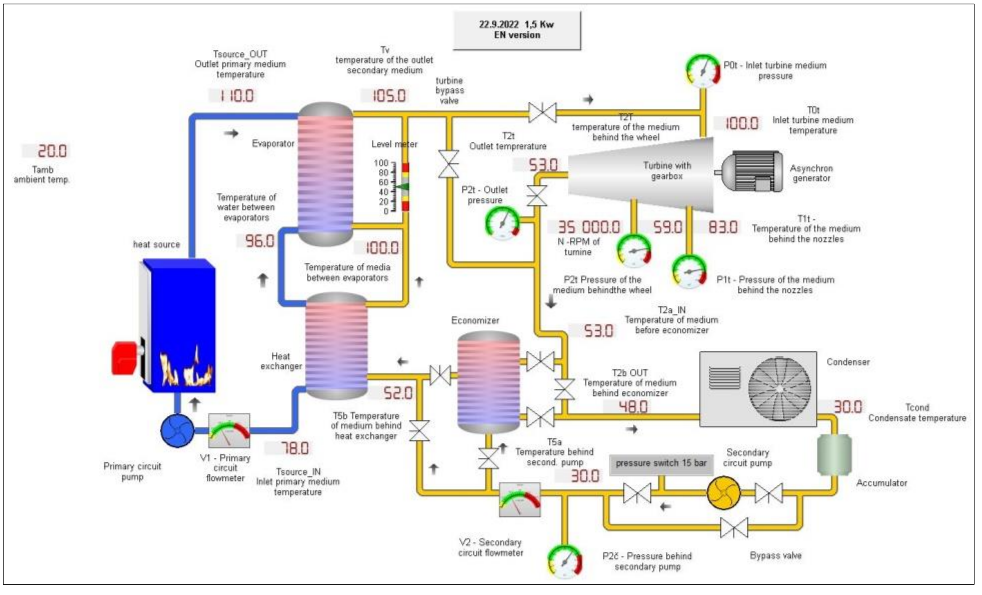

Fig. 4. Schematic of the 1.5 kW µORC test circuit.

3 Digital prototype of micro turbine with magnetic coupling

The development of the entire μORC micro turbine-generator unit was carried out using rigorous digital prototyping methods. The input values for the design of the current part of the micro turbine are shown in Table 2.

Table 2. Design parameters of the flow section of the microturbine

Parameter	Value	Unit
Working medium	R1233zd (E)	
Input temperature at the turbine casing inlet t_0	100	°C
Input pressure at the turbine casing inlet p_0	10,42	bar
Outlet pressure behind the turbine p_2	1,3	bar
Mass flow rate m_T	0,366	$kg.s^{-1}$
Shaft speed n_T	35 000	min^{-1}

The complete nozzle design was performed using the STAR CCM+ CFD system and the Simcenter HEEDS optimization engine using the Sherpa assistant system to select the most appropriate combination of optimization methods. An example of the optimized flow path is shown in Fig. 5.

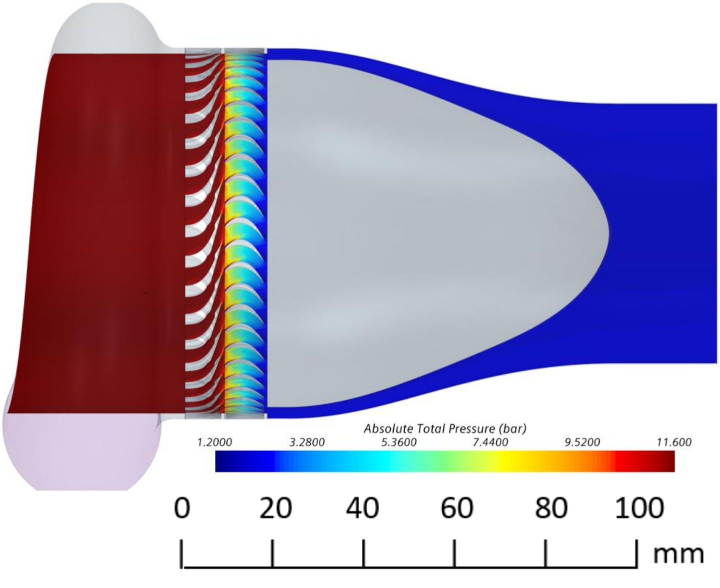

Fig. 5. Flow design of input volute and output diffuser using Simcenter STAR CCM+

Figure 6 shows the fluid flow parameters determined by CFD simulation in STAR CCM+ and the optimized shape of the input volute.

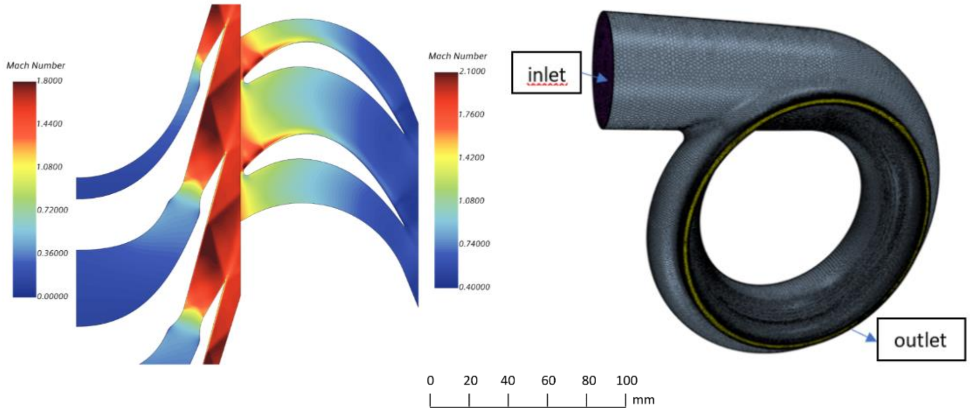

Fig. 6. Computational simulation of the turbine axial action stage and input volute using the CFD program Simcenter STAR CCM+

Furthermore, static and dynamic computation of the impeller and magnetic clutch was performed. The design of the magnetic clutch for high operating speeds of up to 35,000/min proved critical during development. It was necessary to use high-strength materials for the design of the clutch bodies and special magnet mountings due to the high stresses from centrifugal forces.

All static calculations were performed using the FEA method in Simcenter 3D. NX Nastran solvers were used to check the dynamics of the two mass system of the impeller and clutch.

4 Prototype production

The production of the components of the ORC micro turbine unit was carried out with the consistent use of 3D printing methods for the creation of working mock-ups of the unit and also functional parts of the turbine casing moulds. The flow-through parts of the turbine were final machined using 5-axis machining. An example of the printed parts and the final impeller shape is shown in Fig. 7.

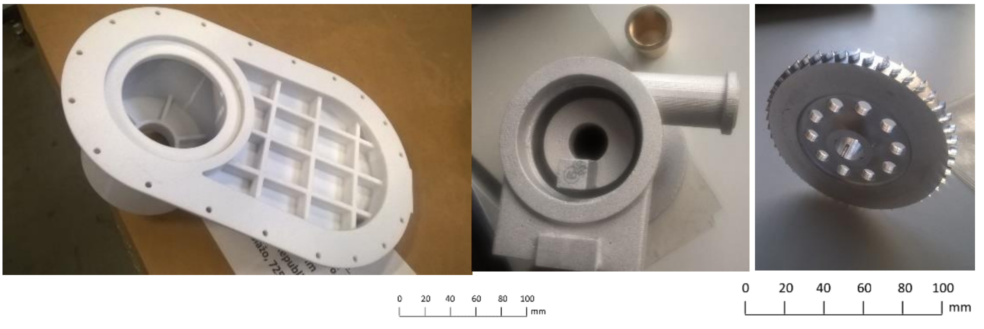

Fig. 7. On the left the gear cover made by 3D printing, in the middle the printed mould for the casing casting and on the right the impeller of the micro turbine after final modification

5 Experimental measurements

The measurements were carried out in a test room where a hot water electric boiler with an output of 18 kW was used as a waste heat source. The ORC micro turbine unit itself and the entire ORC unit at the test site are shown in Fig. 8.

Fig. 8. On the left the micro turbine unit with generator, on the right the complete ORC unit in experimental operation.

The prototype was equipped with more than 30 measuring points each to monitor physical quantities such as pressures, temperatures, turbine speeds, working medium flows, cooling water, evaporator levels, etc. Figure 9 shows the installation of both turbines with sensors and the output of signals to a sub panel of connectors for connection to the central control system (control, data acquisition).

The ORC unit was completely developed, mostly manufactured in cooperation with MCAE Systems. Completion of the circuit, piping connection and filling with the working substance (refrigerant R1233zd(E)) including the supply of the measuring panel and the connection of the sensors was carried out in cooperation with an external partner qualified for working with refrigerants.

In order to measure the power characteristics, MCAE Systems has also developed an electrical load (power resistor) with proportional power control to cover the required power range. The load in Fig. 4 is designed as a set of power resistors that are switched in parallel to the generator output according to the output current (power) requirement. It is designed to be universal for both power variants of ORC units. The regulation is discrete, in 12 steps:

For the ORC 1.5 kWe version from 0W to 1265 W, step approx. 90 W, at an operating voltage of 14 V DC. An example of the measurement record is shown in Fig. 9.

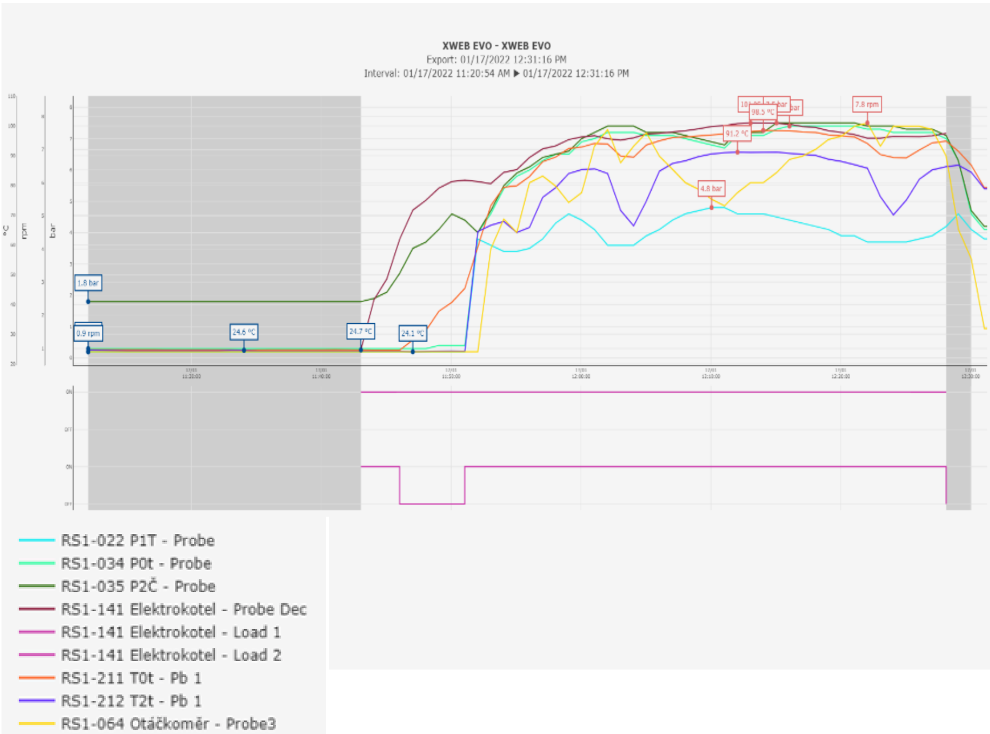

Fig. 9. The measurement record of the ORC unit shows the temperature, pressure and rotational speed.

6 Conclusion

The results of the tests confirmed that the chosen path of the ORC unit concept (we followed up on our utility model registered with the Industrial Property Office of the Czech Republic under no 34240) is correct. In this context, it is necessary to continue the established trend and to further develop the necessary technical and personnel infrastructure, to plan an extensive test programme using the existing very valuable knowledge as well as new opportunities in the field of rapid prototyping, e.g. metal printing, which is available to us, etc.

The tests have verified performance parameters, turbine efficiencies, overall circuit efficiencies, etc. under various anticipated operating modes.

The problems I encountered were of a mechanical nature at the magnetic coupling of the hermetic bulkhead. The magnetic coupling was experiencing defomation in the screw connections holding the magnets and the bulkhead was experiencing increased deflection due to the high temperatures and low temperature resistance of the material used. This has now been replaced by a more temperature and strength resistant type of GRP. The temperature field around the magnetic coupling was unproblematic and did not even reach 1000C. There was no problem with eddy currents due to the non-conductive material of the baffle.

3D printing played a major role in the development of the ORC unit, especially in the preparation of the moulds for the turbine casing casting. Using the mouldable model method. Furthermore, the gearbox body, including the housing, the panel for mounting the connectors of the measuring sensors and other small components of the miroturbine were made by 3D printing.

Further, long-term durability and reliability tests need to be carried out with monitoring of wear and tear of the unit components to gain insights to further improve the functionality and durability of the unit for full commercial use.

The overall behavioural results of the prototypes confirm the achievement of the predicted parameters in the field of μCHP.

For future development of the ORC-based unit, the variety of possible applications and thus the range of variations in unit layout and use and associated development work also needs to be taken into account.

The new product will be offered to end customers through TechSim Engineering's own business activities as well as in cooperation with business partners.

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