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Concept of a test stand for electricity generation from waste heat using wet steam

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Abstract

The paper presents a concept of an innovative test stand for converting waste heat into electricity using wet steam. Two expanders will be tested, i.e. a rotary blower and a scroll compressor, which have been adapted for reverse cycle operation. The main objective of the stand is to verify experimentally the feasibility of the effective use of an innovative wet steam cycle for waste heat recovery. To verify the design assumptions, as well as the stand configuration and parameters, preliminary simulations were carried out in Ebsilon software. The solution innovation lies in using wet steam to enhance waste heat recovery. Wet steam is generated on the test stand by injecting water into saturated steam using a specially designed nozzle system. In this way, steam dryness can be controlled precisely and proper conditions are created for the expander operation. Saturated steam is generated in the boiler installed at the laboratory of the Department of Energy of the Cracow University of Technology. The test stand will enable the system operation and an assessment of the system's potential applications. This will help to improve the energy efficiency of waste heat utilization and reduce emissions.

Keywords: Waste heat; Wet steam; Expanders; Preliminary results of simulation; Test stand design

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1. Introduction

In recent decades there has been a significant increase in the demand for various forms of energy. This increase affects all areas of the economy and is associated with the growth in the world's population and the improvement in the quality of life. Consequently, one of the needs that arise is to implement new distributed generation systems. Therefore, the world literature notes an increased activity in the field of research on new solutions enabling efficient use of various energy sources, including industrial waste heat [1]. The rapid development of the world economy in recent decades is confirmed in [2], which also emphasizes the fact that the recovery of low-temperature waste heat is of high importance for energy savings and emission reduction. However, the recovery faces a number of problems, such as the mismatch between the waste heat supply and demand, or the high investment outlays required for distributed waste heat recovery. The authors of [2] presented the prospects for solving these problems. Woolley et al. presented interesting analyses of waste heat [3]. According to them, the industrial sector consumes a third of global energy, of which up to 50% is ultimately wasted in the form of heat. The problem here is the correct identification of the heat quantity and quality. To solve it, a methodology is proposed for selecting appropriate waste heat recovery technologies and making decisions based on economic benefits. The conclusions resulting from the above publications are also confirmed in [4,5]. The former additionally indicates the capabilities and potential of waste heat recovery in the European Union.

Nomenclature

c – specific heat, kJ/(kg K)
h – enthalpy, kJ/kg
$\dot{m}$ – mass flow rate, kg/h
r – heat of vaporization, kJ/kg
p – pressure, MPa
s – entropy, kJ/(kg K)
t – temperature, °C
x – steam quality

Greek symbols

η – efficiency
Φ – power, kW

Subscripts and Superscripts

c – condensation
g – power generator
in – internal
is – isentropic
m – mechanical
s – steam
w – water
1 – inlet
2 – outlet
$'$ – boiling water
$''$ – saturated steam

Abbreviations and Acronyms

DECUT – Department of Energy of the Cracow University of Technology
ORC – organic Rankine cycle
PE-ORC – partially evaporated organic Rankine cycle
TFC – trilateral flash cycle
WSC – wet steam cycle

Mass and volume flows of waste, as well as temperature levels, are identified. The latter provides a quantitative estimate of global waste heat in various sectors of the economy until 2030. This is combined with an assessment of the environmental impact of waste heat fluxes.

In the literature there are many publications on the use of waste heat, including electricity production. A very popular way of heat utilization is the well-known organic Rankine cycle (ORC), which is widely described in the literature [6]. A review of theoretical and experimental studies on the use of ORC for waste heat recovery is presented in [7]. The paper also includes an analysis of the impact of the cycle configuration, the working fluid, and the operating conditions on the system performance. In many cases, however, ORCs are realized using flammable [8] or toxic [9] agents, the leakage of which is inevitable. A certain level of toxicity and flammability can only be accepted if the leaks are very low. The level of the fluid thermal stability should also be taken into consideration. The literature includes analyses related to various modifications of the organic Rankine cycle. They are mainly theoretical works concerning, for example, the dual-loop ORC for diesel engine waste heat recovery [10], turbine bleeding or regeneration, or both [11]. The analyses carried out in [11] indicate that the ORC integrated with turbine bleeding and regeneration is characterized by the highest heat efficiency.

Another way of utilizing waste heat, widely reported in the literature, is the so-called trilateral flash cycle (TFC). Unlike the ORC, the working liquid in TFC expands from the saturated liquid phase to a two-phase mixture. The significant reduction in exergy losses due to a heat exchanger where no evaporation takes place is the main advantage of TFC. The works in this field are mainly theoretical. In [12], the use of the Engineering Equation Solver is proposed to design TFC. Theoretical energy and exergy analyses are performed for various working fluids, and it is found that the twin-screw expander is the most suitable expander technology for the TFC application. It should be noted here that [13] is one of the first works where twin-screw expanders are indicated as the most suitable option for the TFC operation. A numerical model of a two-phase twin-screw expander and its integration with a TFC system model for low-temperature heat-to-electricity conversion applications are shown in [14]. In contrast to [12−14], in [15] a piston engine is proposed for TFC. In this case, however, it is very important that the liquid should not enter the piston chamber. According to the authors of [15], the biggest advantage of the process is the substantial reduction in exergy losses for the TFC process compared to ORC.

Many papers focus on comparing the performance of ORCs and TFCs. Interesting results are shown in [16], where the electricity generation exergy efficiency is found to be 14−29% higher for TFC compared to ORC. In [17], a solar pond is analysed as a low-temperature heat source for electricity generation. In this case, the results indicate that the ORC energy efficiency is higher than that of TFC.

The few experimental papers available in the literature relate to, for example, a TFC system in which a stationary converging-diverging nozzle with an impulse turbine is used as the expander [18]. The authors of [19] present the results obtained using a prototype system where the function of the expander is performed by a modified twin-screw compressor. An analysis of energy and exergy efficiency is performed using experimental data. The measured efficiency of the twin-screw expander reached about 18%.

The above review of the literature indicates that most theoretical and experimental works are related to the use of the twin-screw expander in waste heat utilization processes. Apart from twin-screw expanders, others are also used, such as vane expanders, scroll expanders and pistol expanders. The comparative assessment of different volumetric expanders presented in [20] confirms that screw expanders are the most suitable devices for waste heat utilization. Considering technical constraints and operational performance, scroll expanders are only slightly inferior to them, and they are also the subject of research and analysis. Du et al. [21] emphasize that due to the lack of efficient low-grade heat recovery technologies, the heat is heavily wasted. They performed a thermodynamic and computational fluid dynamics (CFD) analysis of the scroll expander with respect to a system of energy recovery from a low-grade heat source (127°C) using CO_2. The obtained results were successfully verified on a test stand. A detailed numerical analysis of the impact of various operating parameters on the steady- and transient-state efficiency of the scroll expander is presented in [22]. To obtain an accurate and efficient model of the scroll expander, a method is proposed in [23] that combines the residual ANFIS (adaptive-network-based fuzzy inference system) model with the mechanistic model. The method's high accuracy is confirmed experimentally.

In the literature, it is difficult to find publications on the use of the wet steam cycle (WSC) to convert waste heat into electricity. Being a new technology, WSC has not been sufficiently described yet. WSC should be understood as a thermodynamic cycle in which the expander is supplied with wet steam. In this way, the expansion process in the expander begins and ends in the wet steam region. The partially evaporated organic Rankine cycle (PE-ORC) shows some similarities with WSC [1]. The PE-ORC is a transition cycle between ORC and TFC. The paper [1] is theoretical in nature. However, there are no documented experimental results related to the use of wet steam as a fluid driving the expander. Only occasional information can be found, such as the commercial offer presented in [24], where it is proposed that wet steam energy should be converted into electricity using a twin screw turbine.

An interesting solution is presented in [25]. The report presents the conversion of residual steam into electricity using a rotary blower. To the authors' best knowledge, there are no other studies on the use of the rotary blower in the process of waste heat conversion into electricity.

Considering the literature review presented above, a decision was made to carry out experimental studies related to the use of WSC for the production of electricity from waste heat. Because twin-screw expanders are widely described in the literature, a scroll expander and a rotary blower are proposed for this purpose, as these devices are tolerant of wet steam. Using them to realize a WSC is a new approach to the problem of waste heat utilization. This paper presents preliminary results of calculations and simulations of wet steam cycles, along with a concept of the test stand. Based on the results, a scroll expander, a rotary blower and an alternator with appropriate parameters were selected. The stand will be constructed in the near future at the laboratory of the Department of Energy of the Cracow University of Technology (DECUT).

2. Preliminary computations and simulations

To select expanders and a generator with appropriate parameters, preliminary thermodynamic calculations of selected cycles were performed. The obtained results were compared with the results of simulations carried out using the Ebsilon Professional program [26]. The calculations and the simulations were carried out mainly to select the power of the above-mentioned devices, and to determine the level of steam dryness at their outlet. The input data for the calculations were derived from the steam parameters obtained on the DECUT laboratory current test stand. The stand is equipped, among other things, with a boiler generating mass flow $\dot{m}_s$ = 700 kg/h of saturated steam with a pressure of p = 1 MPa and a temperature of approx. 180°C. The boiler is fired with fuel oil. To obtain wet steam with a set level of dryness, an appropriate mass flow of water with a temperature of about 105°C, taken from the thermal degasser, will be injected into the saturated steam pipeline. The resulting wet steam will then be directed to the expander connected to the generator.

Preliminary calculations were carried out for both expanders, assuming that wet steam expanded to atmospheric pressure at the scroll expander outlet, and to a pressure of 8.5 bar at the rotary blower outlet. Based on commercially available devices, it was further assumed that the rotary blower was fed with the entire mass flow of the generated wet steam, whereas the scroll expander – with about a third.

Selected preliminary calculations and the results obtained therefrom are presented below. Example calculations were performed for both expanders assuming that the steam dryness at their inlet was 0.8. Among other things, the following quantities were calculated: the required mass flow of injection water, the level of the steam dryness at the expander outlet, and the power obtained on the shaft.

2.1. Scroll expander

To obtain wet steam, water with a temperature of approx. 100°C will be injected into the saturated steam produced in the boiler. To heat this water to a saturation temperature (180°C for the pressure of 1 MPa), part of the saturated steam mass flow will condense.

Using a simple power balance equation,

$$\dot{m}_w c_w \Delta t_w = \dot{m}_c r, \tag{1}$$

and a relation describing the steam dryness level (steam quality),

$$x_1 = \frac{\dot{m}_s - \dot{m}_c}{(\dot{m}_s - \dot{m}_c) + (\dot{m}_w + \dot{m}_c)}, \tag{2}$$

the required mass flow of injection water $\dot{m}_w$ = 41.2 kg/h and the mass flow of condensing steam $\dot{m}_c$ = 7.03 kg/h were obtained. These values were obtained assuming that $\dot{m}_s$ = 200 kg/h and x_1 = 0.8.

Next, using the following relations:

$$h_1 = h_1' + x_1 r_1, \tag{3}$$

$$s_1 = s_1' + x_1(s_1'' - s_1'), \tag{4}$$

the enthalpy and entropy of wet steam at the expander inlet were calculated, giving the values of 2374.5 kJ/kg and 5.696 kJ/(kgK), respectively.

The following formula for isentropic expansion:

$$x_{2is} = \frac{s_2 - s_2'}{(s_2'' - s_2')} \tag{5}$$

was used to calculate steam dryness at the outlet of the expander (assuming expansion to atmospheric pressure). The result was 0.726.

Next, using formulae

$$h_{2is} = h_2' + x_{2is} r_2, \quad (6)$$

$$h_2 = h_1 - \eta_{in}(h_1 - h_{2is}) \quad (7)$$

and assuming isentropic expansion and internal efficiency η_{in} = 40%, wet steam enthalpies at the expander outlet were found.

The enthalpy values are 2057.2 kJ/kg and 2247.6 kJ/kg, respectively. The scroll expander internal efficiency is based on [20,27], where the value is given for the steam cycle. According to the authors of [27], the operating capacity of the scroll expander does not depend on the inlet steam dryness. This is a big advantage of such an expander. Owing to it, its usefulness in the case of wet steam, and even in hot water conditions, is increased. The calculated quantities are illustrated in Fig. 1.

The steam dryness at the scroll expander outlet, calculated using the formula

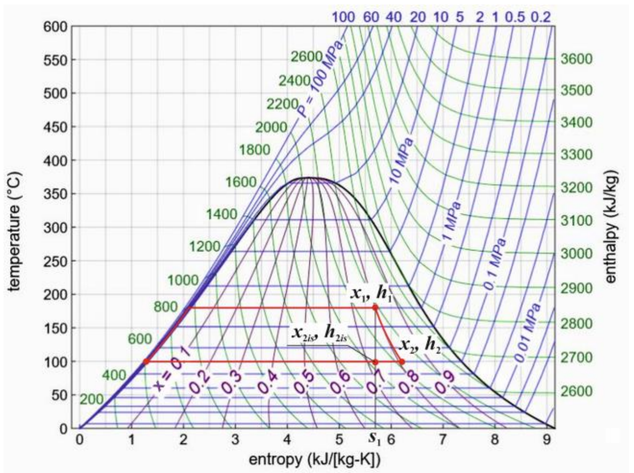

Fig. 1. Scroll expander cycle.

$$x_2 = \frac{h_2 - h_2'}{r_2}, \quad (8)$$

is 0.810.

The available power on the shaft, calculated as

$$\Phi = \frac{(\dot{m}_s + \dot{m}_w)\eta_m (h_1 - h_2)}{3600}, \quad (9)$$

is 7.652 kW. The power achieved in the generator (assuming the generator efficiency of 0.9) totals 6.887 kW.

The results of the simulations performed using the Ebsilon Professional program under the above assumptions are shown in Fig. 2. The simulation data were the parameters of the steam generated in the boiler and the parameters of injection water. The obtained results fully agree with the results of calculations – formulae (1)–(9). Slight discrepancies were observed in the case of the power on the shaft and the power achieved in the generator. This is solely related to the accuracy of the enthalpy and entropy determination.

2.2. Rotary blower

The same calculations were performed for the rotary blower, assuming that $\dot{m}_s$ = 700 kg/h. As there is no literature data on the operation of the rotary blower as an expander, it was assumed that wet steam expanded to a pressure of 8.5 bar and internal efficiency η_{in} = 20%.

Using Eqs. (1)–(9), the following results were obtained:

- injection water mass flow $\dot{m}_w$ = 144.2 kg/h,
- condensing steam mass flow $\dot{m}_c$ = 24.6 kg/h,
- wet steam enthalpy at the expander inlet h_1 = 2374.5 kJ/kg,
- wet steam entropy at the expander inlet s_1 = 5.696 kJ/(kg K),

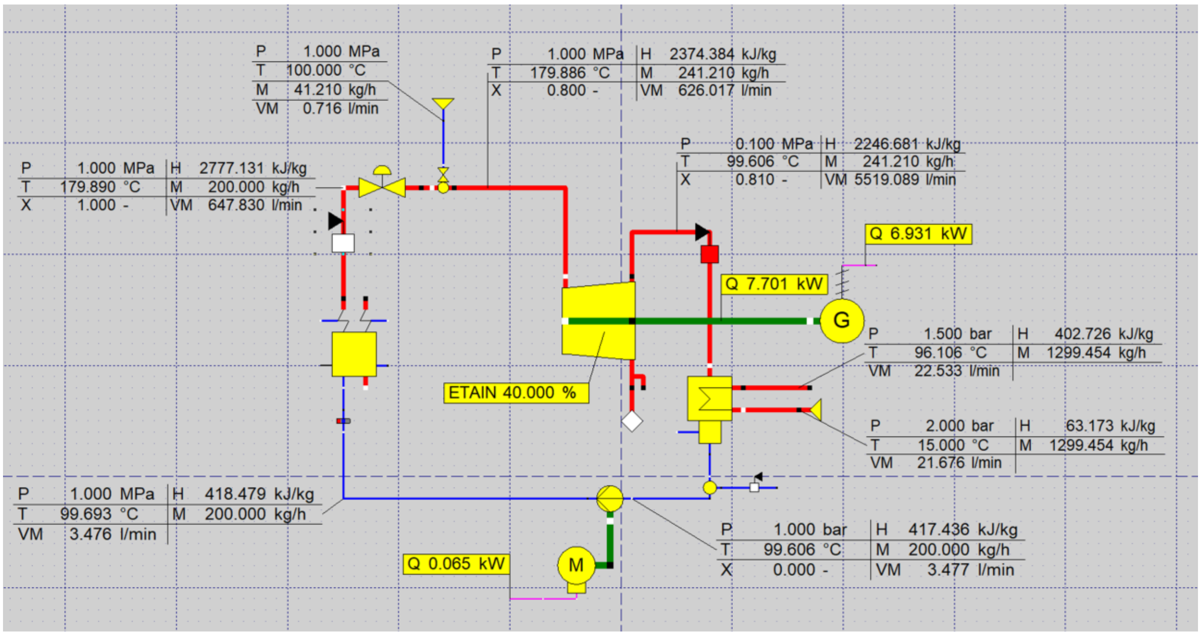

Fig. 2. Ebsilon Professional simulation of a cycle realised using a scroll expander.

- steam dryness at the expander outlet x_{2is} = 0.793 (for isentropic expansion),
- wet steam enthalpy at the expander outlet h_{2is} = 2348.7 kJ/kg (for isentropic expansion),
- wet steam enthalpy at the expander outlet h_2 = 2369.7 kJ/kg (assuming η_{in} = 20%),
- steam dryness at the rotary blower outlet x_2 = 0.803,
- power on the shaft Φ = 1.013 kW,
- power achieved in the generator (assuming the generator efficiency of 0.9) Φ_g = 0.912 kW.

Selected results of the calculations are shown in Fig. 3. The results of the simulations carried out in the Ebsilon Professional program are illustrated in Fig. 4. The simulation input data were the rated parameters of the boiler steam and the parameters of injection water. As in the case of the scroll expander, the results fully agree with the results of calculations. Like before, slight discrepancies were observed in the case of the power on the shaft and the power achieved in the generator.

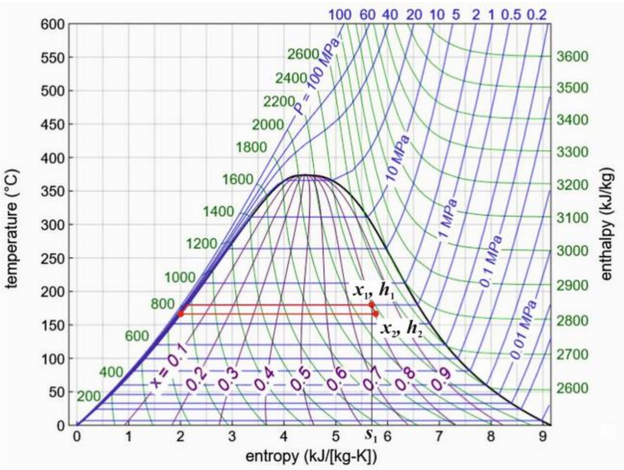

Fig. 3. Rotary blower cycle.

3. Test stand design

The stand design is based on the oil-fired boiler already existing at the DECUT laboratory. Its view is shown in Fig. 5. As previously mentioned, the boiler rated output is 700 kg/h of saturated steam with a pressure of 1 MPa.

Fig. 5. View of the boiler and its equipment.

Based on the calculation and simulation results presented in Section 2, the following devices were selected for experimental studies:

- oil-free scroll compressor (Fig. 6 and Table 1),
- rotary blower (Fig. 7 and Table 2),
- alternator (Fig. 8 and Table 3).

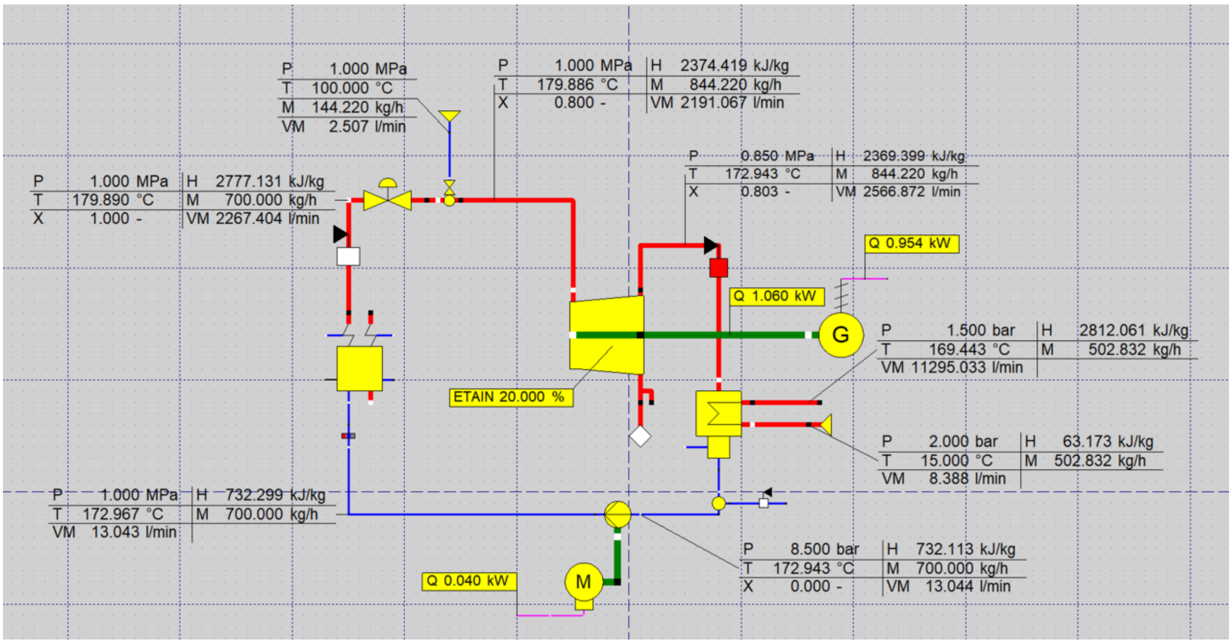

Fig. 4. Ebsilon Professional simulation of a cycle realised using a rotary blower.

Fig. 6. View of the selected oil-free scroll compressor.

Fig. 7. View of the selected rotary blower.

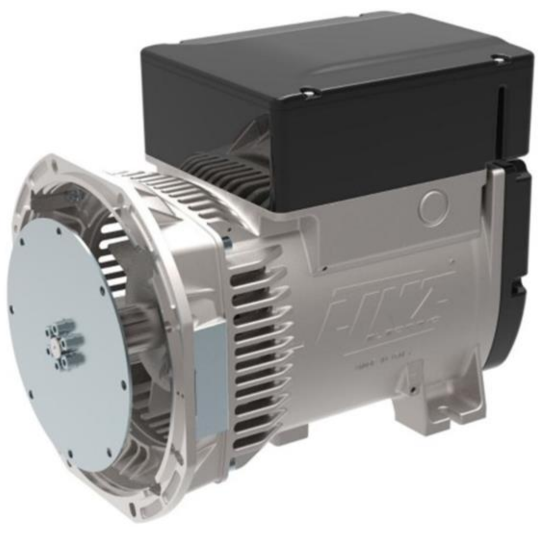

Fig. 8. View of the selected alternator.

Table 1. Selected parameters of the scroll compressor (HitachI SRL-7.5CB).

Parameter	Value	Unit
Maximum working pressure	10	bar
Steam volume flow	~0.7	m^3/min
Power	7.5	kW
Rotational speed	3100	min^{-1}

Table 2. Selected parameters of the rotary blower (Kaeser Omega 42P).

Parameter	Value	Unit
Rated air volume flow	15.91	m^3/min
Minimum rotational speed	900	min^{-1}
Maximum rotational speed	4800	min^{-1}

Table 3. Selected parameters of the alternator (Alternator E1S13S A/4, three-phase synchronous alternator with brushes; compound, 4 poles).

Parameter	Value	Unit
Rated power at 50 Hz	8	kVA
Rated power factor	0.8	–
Air flow requirement	5.4	m^3/min
Maximum over speed	2250	min^{-1}
Frequency	50	Hz
Series star voltage	400/230	V
Efficiency	~85	%

A diagram of the extension of the existing test stand for experimental testing of the selected devices (a scroll compressor and a rotary blower adapted for reverse cycle operation) is shown in Fig. 9.

The stand will also be equipped with a data acquisition system. The following quantities will be measured and collected: the wet steam mass flow, the fluid pressure and temperature at the inlet and outlet of the expanders, rotational speed at different values of the wet steam volume flow, and the amount of generated electricity.

The selected devices (the scroll compressor and the rotary blower) were preliminarily tested for operation in a reverse cycle. Air compressed up to approx. 5 bar was used for this purpose (Fig. 10). No quantity was measured during the tests; the correctness of the device operation was only assessed visually and acoustically.

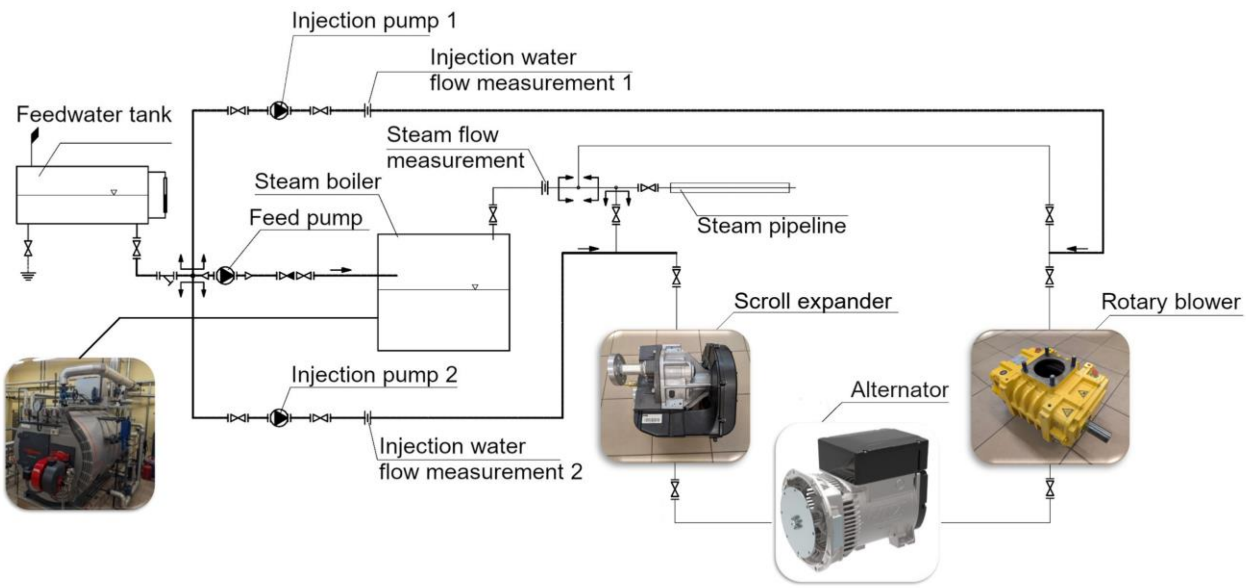

Fig. 9. Diagram of the current test stand at the DECUT laboratory, including the wet steam generation system, expanders and alternator.

Fig. 10. Preliminary tests of the selected devices during their operation in a reverse cycle.

4. Conclusions

The paper presents the concept of a test stand to empirically confirm the possibility of effective utilization of an innovative WSC for waste heat recovery. As part of the research work, it is planned to develop a system enabling the implementation of cycles not used before and using wet steam as a working fluid in the temperature range of approx. 150°C to approx. 450°C. This requires the use of wet steam-tolerant expanders. The solution proposed herein is truly universal and will have an impact on the reduction of CO_2 emissions into the atmosphere.

A vast majority of the waste heat recovery systems now in use are based on well-known ORC systems. They make use of refrigerants/low-boiling liquids. Today's refrigerants are being replaced by agents that have a less harmful impact on the environment. These substitutes have a low global warming potential (GWP), but some are still harmful, flammable or toxic. In the planned solution, the working fluid is water/steam, and it does not have the adverse properties of refrigerants.

Based on a detailed review of the literature, it was possible to select the scroll compressor and the rotary blower for experimental studies. Obviously, these devices are originally intended for increasing gas pressure at the expense of the supplied electrical energy. After minor modifications, these machines will be fed with wet steam and generate mechanical energy used to drive the generator. The idea of such use is based on the already known trilateral cycle, in which boiling water is fed into an expander where evaporation occurs during the expansion process. As part of this work, it is proposed that the above-mentioned cycle should be developed further for the heat recovery technology by implementing:

- WSC for a wide range of wet steam quality,
- TFC enhancement by the supply of wet steam,
- the use of a wet steam-tolerant expander.

The proposed WSC combines the advantages of the conventional saturated steam process with the thermodynamic advantages of the TFC process.

Preliminary calculations and simulations enabled the selection of a scroll compressor, a rotary blower, and an alternator with appropriate parameters, adapted to the parameters of the saturated steam generated in the boiler installed at the DECUT laboratory. In the near future, the existing test stand will be expanded to the necessary extent. The extension will include, among other things, the generation of wet steam with a set level of dryness, the connection of a scroll compressor, a rotary blower and an alternator, and a data acquisition system.

Some risks that may occur during the stand operation are obtaining wet steam at a set dryness level and adapting the expanders to wet steam.

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