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Experimental investigation on a rotodynamic pump operating in the cogeneration system with a low-boiling working medium

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Abstract

The article presents the research carried out on the circulating rotodynamic pump (peripheral pump) operating in the organic Rankine cycle with or without regeneration. The low-boiling solvent HFE7100 was used as the working fluid. Its boiling point is around 61 °C at atmospheric pressure. An expansion valve, which simulated the operation of an expansion machine, was used to load the tested pump. The flow characteristics were given for the working media: a solution of glycol and HFE7100 in the condenser, thermal oil and HFE7100 in the evaporator and HFE7100 in the regenerator. The research results concerning the PK70 pump operating in an ORC cycle are reported for the HFE7100 temperature range 15-60 °C and the dynamic viscosity range of 0.132 to 0.66 mPa s. The maximum flow rate and pressure of the pump during its operation in the ORC system were assessed. The analysis of the results demonstrates that the maximum efficiencies of the pump operating with or without regeneration were 44% and slightly below 37%, respectively. The impact of the selected physicochemical parameters of the working mediums on the pressure drops occurring in the ORC cogeneration installation was discussed. Based on the research conducted and the measurement results, the possibility to apply a PK70 unit as a circulating pump for the working medium in an ORC cycle was checked.

Keywords: Organic Rankine cycle; Micro-CHP; Rotodynamic peripheral pump; Low-boiling medium; HFE7100

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Nomenclature

c_p	–	specific heat of the working fluid, J/kg K
g	–	gravitational acceleration, m/s^2
h	–	level difference between the discharge port and the suction port, m
H_U	–	net pump delivery head, m
m	–	mass, kg/s
$\dot{m}$	–	flow rate of the fluid
N_U	–	discharge pressure of the pump, N/m^2
P_U	–	net power of the pump, W
p_s	–	pressure measured at the pump's suction port, N/m^2
p_t	–	pressure measured at the pump's discharge port, N/m^2
q_V	–	actual flow rate of the pump, m^3/s
Q	–	thermal power, W
t_s	–	liquid temperature at the pump inlet, K
t_t	–	liquid temperature at the pump outlet, K
u_s	–	average liquid speed at the pump inlet, m/s
u_t	–	average liquid speed at the pump outlet, m/s
x	–	quality, –
ρ	–	fluid density, kg/m^3
γ	–	specific gravity of the fluid, N/m^3

1 Introduction

In the last decade, much attention has been paid to systems powered by renewable energy sources (RES), not only within but also outside the European Union (EU). Such systems are to contribute to reducing fossil fuels consumption and improving the natural environment by limiting emissions of greenhouse gases. According to the forecast by 2030 the global usage of energy will go up by 71 pp. [1]. One suggestion is to apply the organic Rankine cycle (ORC) systems which can contribute to the reduction of greenhouse gases emitted as a result of combustion of fossil fuels. Recent studies on heat recovery in selected industrial sector in the EU have shown that up to about 20 000 GWh of thermal energy (which represents a saving of 7.6 Mt of CO_2) can be recovered by the application of ORC technology [2]. Therefore, strong emphasis is on waste heat recovery, and in particular on low temperature heat recovery (i.e., up to approx. 250 °C), so that it can be used for electricity or cold production. The ORC cogeneration systems operating with low-boiling mediums, the selection of which depends on multiple factors, are a particularly appropriate means to accomplish this task. Apart from heat exchangers, expansion devices (e.g., vapour turbines, scroll/screw expanders), fittings, measuring and control equipment, pumps utilizing a working fluid are essential in all types of ORC systems [3–5]. A circulator pump is an essential part of any ORC system because it has a substantial impact not only on the operating parameters of a working medium (i.e., pressure and flow rate) but also, in particular, on the gross electrical power and efficiency of a whole cycle. Ensuring appropriate parameters of a working medium directly affects the operation of expansion devices, and hence their efficiencies. Therefore, the selection of the most suitable and efficient pump for ORC installation is a very important issue, but also a very demanding one. Low-boiling mediums are noticeably less viscous than water, making their lubricating properties insignificant. Oil-free devices should be used in ORC systems which ensure that a working medium's properties remain unchanged. Most manufacturers provide technical parameters for pumps assuming water as a working fluid. The application of low-boiling mediums has a major impact on the operating parameters of a pump. So, there is a need to conduct experimental tests on the pump in order to examine its operational performance. There are many descriptions in literature of the ORC installations equipped with various circulator pumps utilizing different working fluids.

For instance, Chougule *et al.* [6] conducted the experimental investigation of a 100 kW ORC system equipped with twin screw expander. A positive displacement pump was applied in the working medium (R245fa) cycle. The experimental investigation was conducted with maintaining a superheat vapour condition (degree of superheat 20 °C) at expander inlet. The expander's isentropic efficiency was in the range 60–80% and 80–88% at a constant shaft speed of 1500 rpm and 2000 rpm, respectively. The authors concluded that the variations in the expander efficiency are caused by varying degree of superheat of the working medium. The cycle was equipped with an oil pump used for lubrication of the expander's bearings. The oil separator was used to separate the oil which got mixed with the working fluid and to circulate it back to the expander. The pressure drop observed across the oil separator was in the range of 0.24–0.26 MPa, which caused lower power output of the expander. Moreover, the oil mixed with the working medium resulted in the reduction of condenser's efficiency.

Nautiyal *et al.* [7] carried out the experimental research on a centrifugal pump as an alternative to a turbine generating electricity in small and microhydropower systems. The system uses the rotodynamic pump (KC 100-65-315) with the following basic characteristics: specific speed 18, delivery head 32.8 m, flow rate 0.0148 m^3/s and input power 8.18 kW. The pump was connected to a 12.5 kVa synchronous generator with the maximum rated speed of 1500 rpm. The efficiency of the turbine was about 60% and it was 5% lower than during the operation in pump mode.

Landelle *et al.* [8] performed research on a 10 kWe supercritical ORC system with the R-134a medium. The researchers stated that a circulator pump is a key element in supercritical systems powered by low-temperature energy sources. The cycle utilized a diaphragm pump (model G03X) that was connected to a frequency converter. The maximum efficiency of the pump driven by an induction motor was approximately 41%. The pump losses were about 450 W for the shaft output power of about 1750 W. At the differential pressure of 0.30 MPa and the rotational speed in the range from 342 rpm to 632 rpm, volumetric efficiency of the pump oscillated between 92% and 95%. The reciprocating pump efficiency and cycle exergetic efficiency decrease if the load increases.

Ratajczak [9] presented the results of the analysis focusing on operational parameters of the rotary-lobe pump (model CPA-5) depending on rheological parameters of the transported fluid. The increase in fluid viscosity reduced the volumetric efficiency of the pump and had a significant impact on leaks from the discharge side to the suction side and internal friction of the liquid. The total efficiency of the pump unit depended on the rotational speed, flow resistance in the pipeline, and in particular on viscosity of the working liquid. For instance, as the discharge pressure increased from 0.2 to 0.57 MPa, there was a decline in the volumetric flow rate of the medium (from 580 m^3/s to 550 m^3/s) and an increase in power consumption by the pump (from 475 W to 650 W). The pump efficiency declined with an increase in viscosity (from 10 Pa s to 41 Pa s) and in rotational speed (from 8 rpm to 32 rpm). For example, for the speed increase from 8 rpm to 32 rpm at the viscosity of 10 Pa s the pump efficiency dropped by approx. 16 pp. (from 46% to 30%).

Ntavou *et al.* [10] carried out the experimental investigation of an ORC system with two scroll expanders connected in series, using R245fa as working fluid. The net maximum electrical capacity of this ORC system was 10 kW, when supplied with 100 kW of thermal power at the working medium temperature of 130 °C. An axial piston pump characterized by high discharge pressure at low flow was applied as circulator pump utilized to circulate the working medium. The measurements have shown that the maximum total electric power of both expanders was 6 kWe at the thermal power of 70 kWt. The maximum thermal efficiencies of the cycle was 7.2%, and the maximum isentropic efficiency of the expander was 66%. A decrease in the thermal and isentropic efficiencies was observed with the increase of rotational speed of the pump. The isentropic efficiency decreased from 55% to around 20% with the increase of pump speed from 20 Hz to 50 Hz.

Darakhshan and Nourbakhsh [11] conducted theoretical analysis and experimental research of the centrifugal pump operating as expander to produce electricity. The pump's operating parameters were as follows: maximum input turbine shaft power 20 kW, maximum head 25 m, maximum discharge 0.12 m^3/s and specific speed 23.5 (m, m^3/s). The minimum efficiency of the pump operating as turbine was 30% and was obtained for the following parameters: head number 5, discharge number 0.01 and power number 0.5. The maximum pump's efficiency reached about 79% and occurred at the following parameters: head number 7.8, discharge number 0.065 and power number 0.8.

Minea [1] carried out experimental research 50 kW ORC system equipped with a single-stage twin screw expander. The ORC module was connected to a 700 kW electrical boiler, simulating the waste (or renewable) heat source. A multistage pump was applied as circulator pump and operated with HFC-245fa working fluid. The rotational speed of the pump was adjusted by a variable frequency inverter (from 0 to 60 Hz). The rotational speed was adjusted in such a way to achieve a relatively small working medium's superheating amounts (i.e., not exceeding 5 °C) at the evaporator outlet. The author concluded that the working medium's degree of superheat dropped at the expander inlet port, as medium moisture level increased. Moreover, according to the author's opinion, volumetric machines are not very susceptible to moisture and are capable of operation with a wet medium at the expense of a fall in ORC system efficiency. The net heat-to-electricity energetic efficiency reached 7.57% and the maximum net power output was 39.9 kWe. The maximum input power of the pump (operating with HFC-245fa fluid) did not exceeded 3% of power produced by the expander. The power efficiency and exergetic efficiency of the system increased from 6.62% to 7.57% and from 3.95% to 4.43%, respectively, with an increase in temperature of the working medium. The increasing of superheating degree, at constant operating parameters of the heat source, was pursued by means of reducing flow rate of the working medium. The author of the paper noted that it was necessary to determine an optimum rotational speed of the circulator pump in order to achieve an adequate superheating conditions for the working fluid.

Muhammada *et al.* [2] presented research results of the 1 kWe system based on ORC technology which was powered by waste heat, using vapour which pressure was in the range 0.1–0.3 MPa. The system used R245fa as working fluid and a scroll expander (model E15H22N4.25) that was coupled with a 1 kWe generator. Maximum thermal efficiency of the ORC system was 5.75% and maximum expander's isentropic efficiency amounted to 77.74%. It was stated that: a rise of working fluid's superheating by 1 °C (at expander inlet) lowers thermal efficiency of the system by 0.021%. The T series gear pump (manufactured by Tuthill), magnetically coupled to 0.75 kW three-phase motor, was applied as circulator pump in the ORC thermal cycle. Maximum gross electrical output of the expander (1016 W) was observed at a pressure ratio of 10.05. Thermal efficiency and electrical output of the expander rises, as pressure ratio increases. However, the expander's isentropic efficiency decreases with an increase in pressure ratio. The highest (expander's) isentropic efficiency observed was 77.74% at pressure ratio of 6.1, while the lowest was 57.97% at pressure ratio of 10.08.

Bartolini and Romani [12] carried out the theoretical analysis of a peripheral pump in terms of energy efficiency. Peripheral machines are classified as fluid-flow machines according to their functional properties. They are used in the area of applications between volumetric pumps and radial flow pumps. The authors concluded that an increase of the overall efficiency of the pump is avaiable by optimization of the inlet angle for very high values of the volumetric flow rate.

Hasmatuchi *et al.* [13] conducted the experimental investigations of a radial pump-turbine comprising two 400 kW centrifugal pumps in serial connection which provide a maximum head of 100 m. The authors stated that the pressure fluctuation is very low at the highest efficiency obtained. A substantial increase of the pressure was observed within the stator while it was minimum in the draft tube (which resulted from the pump channel geometry).

It follows from the above literature review that a wide variety of pumps is used in ORC cogeneration systems and their selection depends mainly on the type of working medium and expansion device. Power consumption and efficiency of the organic Rankine cycle changes according to the pump applied. Type of pump also has an impact on pressure level and its fluctuation, flow rate, net electrical efficiency of the system and superheating degree of the working medium. Improper pump operation has a negative effect on expansion device's functioning and thus on the entire ORC thermal cycle. Therefore, selection of a suitable pump is a key issue for any cogeneration system.

2 Test bench

The ORC test bench, located on the premises of the Micro-CHP Power Plant Laboratory, is composed of the three basic cycles: a heating cycle, a cooling cycle and a working fluid cycle. The heating cycle consists of a group of oil pumps and two independent heat sources: a multifuel boiler and a set of two electric thermal oil heaters which can operate independently or in series. The HFE7100 working cycle contains the following elements: evaporator, condenser, regenerator, circulator pump (for a working medium), measuring devices (e.g., flowmeters, thermocouples, pressure transducers, differential pressure transducers) and supporting structure (test bench frame). The photo of the ORC test bench is presented in Fig. 1. The ORC installation can operate in two modes, as a cy-

Figure 1: ORC test bench at the laboratory belonging to the Szewalski Institute of Fluid-Flow Machinery PAS in Gdańsk.

cle with regeneration (regenerative shell-and-tube heat exchanger) and as a cycle without regeneration (i.e., the regenerative heat exchanger is separated from the cycle by the valves). Measurement schemes of the organic Rankine cycle, with and without regeneration of the working medium, are shown in Figs. 2a and 2b, respectively.

The measurement points that record pressure, temperature and flow rate of the working mediums are indicated on both schemes. The points marked with numbers from 1 to 8 were used to describe changes in a thermodynamic state of the working fluid.

2.1 Peripheral rotodynamic pump PK70

The selection of the circulator pump was based on the following assumptions: pump working pressures of up to 1 MPa at a liquid flow rate of around 0.16–0.17 kg/s, pump can be operated continuously without the need for lubrication to prevent mixing of a working fluid and a lubricant, pump and its sealing elements should be resistant to solvents (since the working medium HFE7100 has solvent properties), operating temperature of the liquid should not be higher than 60 °C, cost of the device should be as low as possible. On the basis of the above requirements, the peripheral rotodynamic pump PK70 manufactured by Pedrollo has been chosen. The pump, along with its basic technical data (relating to water),

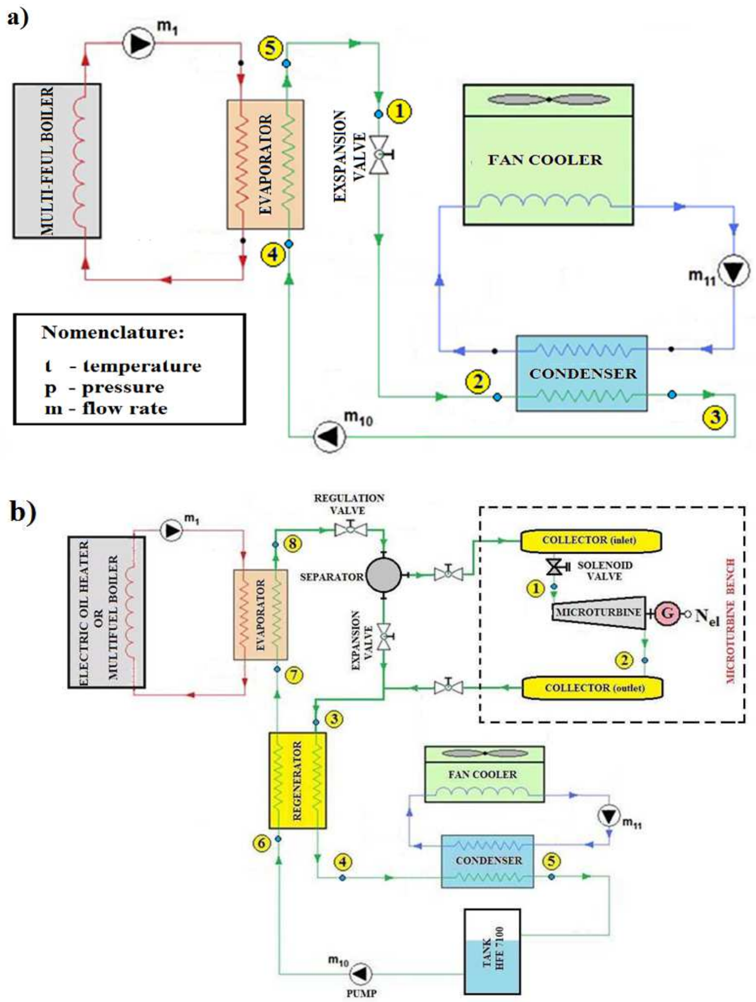

Figure 2: Measurement scheme of the ORC: a) without regeneration, b) with regeneration.

is shown in Fig. 3.

Commercial specialized software (e.g., ASPEN or EES) plays a key role in the design optimization of ORCs. It is essential that physicochemical characteristics of mediums found in computer applications are consistent with the ones stored in producer's databases, which allows to obtain more accurate results. For example, viscosity and density of a working medium significantly influence the pump selection. Low viscosity of a medium restricts the availability of oil-free pumps

flow rate up to	0.8 kg/s
max. liquid temperature	60 °C
head up to	65 m
manometric suction lift up to	8 m
max. sound level	70 dB(A)
max. rotational speed at 50 Hz	2900 rpm
operation mode	S1- continuous
nominal engine power	0.6 kW
weight	9.9 kg
price	€167

Figure 3: Technical data of the peripheral rotodynamic pump PK70 produced by Pedrollo [14].

that can be applied in ORCs. However, net pump delivery head decreases with an increase of medium density. Therefore, in the next section more attention is given to the HFE7100 medium and its selected physicochemical properties.

2.2 Selected properties of the HFE7100 working medium

The HFE7100 medium is a hydrofluoroether, methoxy-nonafluorobutane (with the molecular formula $C_4F_9OCH_3$). It has no ozone depleting potential, which allows its use as a substitute for a medium adversely affecting the environment. Features like excellent chemical and thermal resistance, incombustibility and low toxicity make it possible to use this product as a safe heat-transfer fluid for a variety of industrial applications (e.g., in ORC cogeneration systems) [15]. In choosing the circulator pump for ORC system, viscosity and density of the working medium, as already mentioned, are important parameters. Pump manufacturers provide operating parameters for water as working medium. Therefore, the awareness of properties of the working medium is a prerequisite of the correct choice of circulator pump, and as a consequence the proper operation of the whole ORC cogeneration system.

Figure 4 includes the representation of the liquid density curve as a function of temperature (for HFE7100 medium), according to different sources. The density of the HFE7100 liquid at 0 °C reported by Rausch *et al.* [16] is higher by 2.3% than the value stated by the producer 3M Novec [17], and in the case of data provided by ASPEN software the density is higher about 2.7%. However, almost 100% parity was observed for the data taken from the Engineering Equation Solver (EES) software. The density of the HFE7100 liquid at 90 °C specified in the EES software is lower by 3.7% than the manufacturer's data, while the others data sources demonstrated extremely high conformity with the reference data.

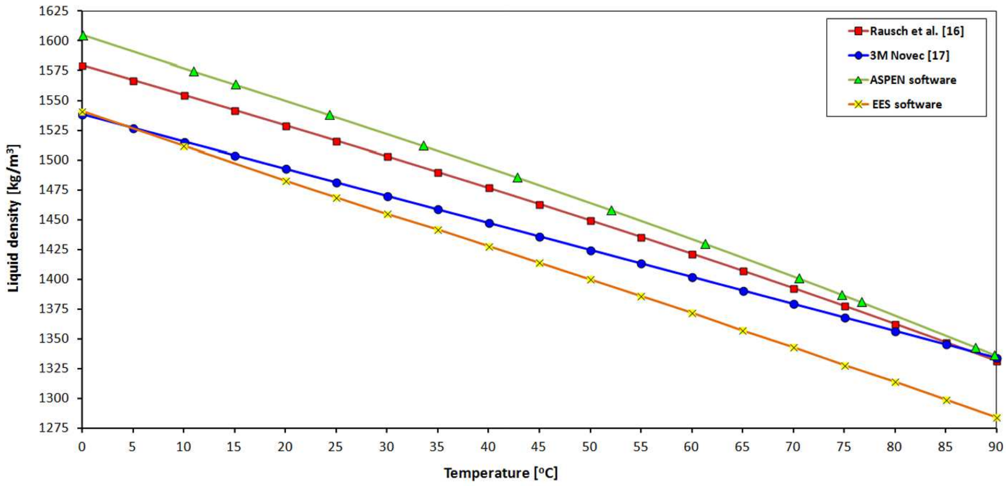

Figure 4: Density vs. temperature (working liquid HFE7100).

Figure 5 shows the HFE7100 kinematic viscosity curves as functions of the fluid temperature, created on the basis of different sources of information.

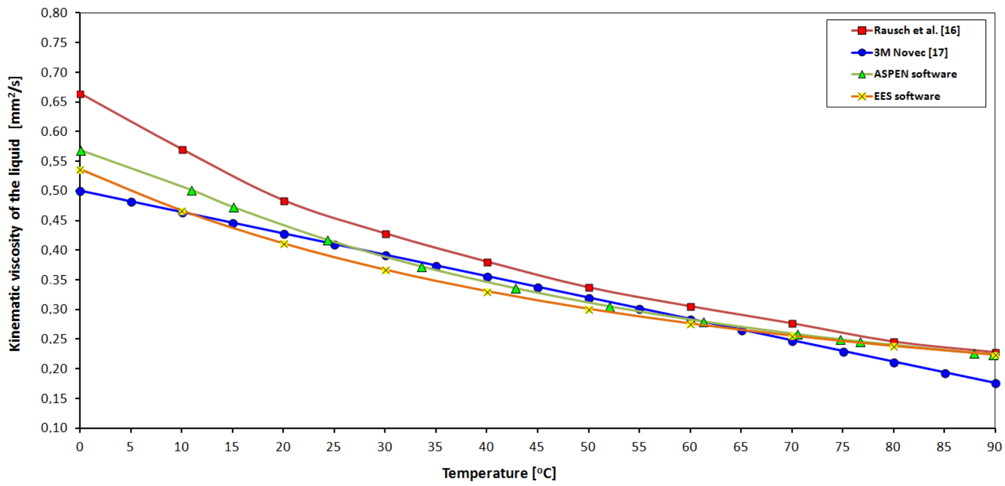

Figure 5: Kinematic viscosity vs. temperature for the working liquid HFE7100.

The viscosity of the HFE7100 fluid at 0 °C provided by 3M Novec [17] is lower from that found in the other sources of information. The viscosity value provided by Rausch *et al.* [16], ASPEN and EES software was higher than the reference value (32.8%, 13.7%, and 7.3%, respectively). As for the viscosity at 90 °C, the reference value was lower by about 24% from that found in the remaining sources of information.

The foregoing analysis demonstrated that the HFE7100 density difference, according to the various databases, does not exceed 4%, which has only a marginal impact on the pump delivery head. In the case of kinematic viscosity, its value varied greatly depending on the data sources and was sometimes even as much as 33%. Such a great difference in kinematic viscosity can result in faulty operation, premature wear and even permanent damage of the pump. Furthermore, viscosity has a significant impact on the pump's efficiency and, therefore, the efficiency of the entire ORC cogeneration unit. That is why when choosing the pump it is necessary not only to consider all the essential parameters (i.e., delivery head, capacity, max. working pressure or efficiency), but also to pay close attention to viscosity range of the working medium.

3 Research results and measurement data analysis

The mass flow rates of the working medium as a function of time recorded during the pump operation in the ORC system with/without regeneration were shown in Figs. 6a and 6b, respectively. In order to ensure the steady state during the measurements and determine the heat losses of the ORC installation [18], the pump test took approx. 130 min. in the ORC cycle operation mode with regeneration, and approx. 120 min. when operated without regeneration. The characteristics relating to the flow rate of the working medium is very important, for many reasons: first, it enables the behaviour of the pump to be observed when the load is being increased or decreased; secondly, it provides information about the dynamic performance of the control system; thirdly, the flow rate directly affects the power output of the pump (Fig. 11), and the electric power generated by an expansion device (e.g., a microturbine, a scroll expander); fourthly, by knowing the time-dependency of the flow rate and the physicochemical parameters of a working medium (temperature, pressure) the electric power produced by an expansion device can be estimated.

During the pump tests carried out in the thermal cycle with regeneration (i.e., within 60 min), the working medium's flow rate was kept within the range of 0.155–0.160 kg/s while increasing the load. The flow rate was adjusted by means of a frequency converter connected to the pump motor. Changes in pump load were achieved by an expansion valve throttling the working fluid, HFE7100 flow. It was established that the difference in the pump load of around 0.05 MPa was

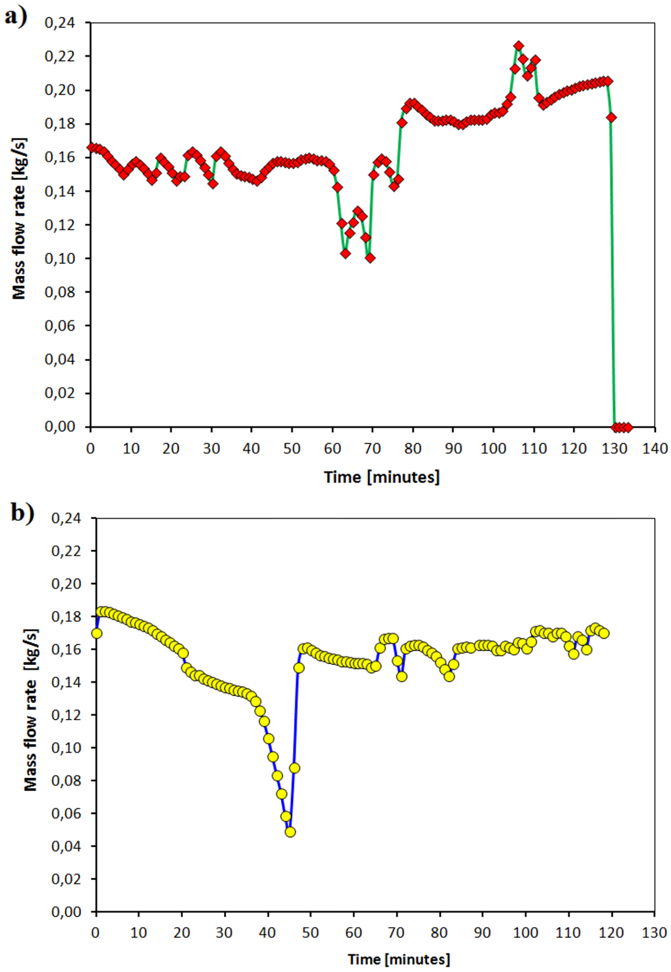

Figure 6: Mass flow rate of the working medium vs. time, during operation of the peripheral pump in the ORC: a) with regeneration, b) without regeneration.

accompanying by a drop of HFE7100 flow rate of approx. 0.01 kg/s. Then the pump was loaded without increasing the flow rate of the working medium. At a flow rate of approximately 0.1 kg/s, the pump started showing the external symptoms of cavitation, i.e., the increased noise and vibration levels and the flow rate fluctuated within the range of 0.1 to 0.12 kg/s (this phenomenon occurred between the 60th and 70th minute of the measurement). During the next time period, i.e., between the 70th and 130th minute, it was determined that the maximum flow rate of the working medium was approx. 0.23 kg/s at a maximum forcing pressure of approx. 0.61 MPa. In the ORC cycle without regeneration (see Fig. 6b), within the first 45 min, the pump was loaded causing a decrease in flow rate from 0.18 kg/s to 0.05 kg/s. It is ascertained that the pump cavitation occurred at the flow rate of around 0.5 kg/s. During the time period between the 50th and 120th minute, the pump was loaded by increasing the discharge pressure up to 0.59 MPa. During the pump loading, the HFE7100 flow rate was maintained at 0.165 kg/s. In the case of ORC with regeneration the working medium's flow rate value oscillated from 0.10 kg/s to 0.23 kg/s, while in the case without regeneration this value ranged from 0.05 kg/s to 0.18 kg/s. It was found that the peripheral pump is capable of providing optimal flow of the working medium (i.e., 0.16–0.17 kg/s) independently on the operation mode of the ORC system (with or without regeneration).

An important element of test bench investigation is to determine pressure drops in its individual parts so as to confirm whether or not the computed flow resistance is achieved. As noted above, medium's physicochemical properties change as the temperature changes. Therefore, it has been decided to determine pressure drops in the heat exchangers for a selected temperature range of the working mediums (thermal oil, HFE7100 and glycol). The pressure drops of the working mediums as a function of temperature, which were measured in the evaporator operating in the ORC installation with/without regeneration, are shown in Figs. 7a and 7b, respectively. For the purposes of determining the trend line values for pressure drop in the evaporator during the flow of the thermal oil, the polynomial regression was applied (the polynomial function of degree 4 – continuous line). In the case of HFE7100 medium, the linear regression was used (broken line). In the operation mode with regeneration, the pressure drop (from 36 kPa to 9 kPa) occurred with the increase of oil temperature from 20 °C to 130 °C. Regarding the operation mode without regeneration, the pressure dropped from about 30 kPa to about 10 kPa for the same rise in temperature. A significant drop pressure of the thermal oil in the evaporator was caused by a very high change in the thermal oil's viscosity. The dynamic viscosities of the oil having a temperature of 20 °C and 130 °C are 150 mPa s and 2.4 mPa s, respectively (the latter viscosity value is more than 62 times lower than the former). When designing an oil cycle, it is important to ensure this issue is not neglected, particularly where the installations are exposed to low temperatures. Since a flow resistance in the case of oil can be very high, it may cause problems with the startup of the heating installation in ORC cogeneration system, and in some cases may even lead to the oil pump being damaged. At high flow resistances, an oil pump needs a huge starting current. Therefore, the pump's electric drive may be damaged if the starting time is too

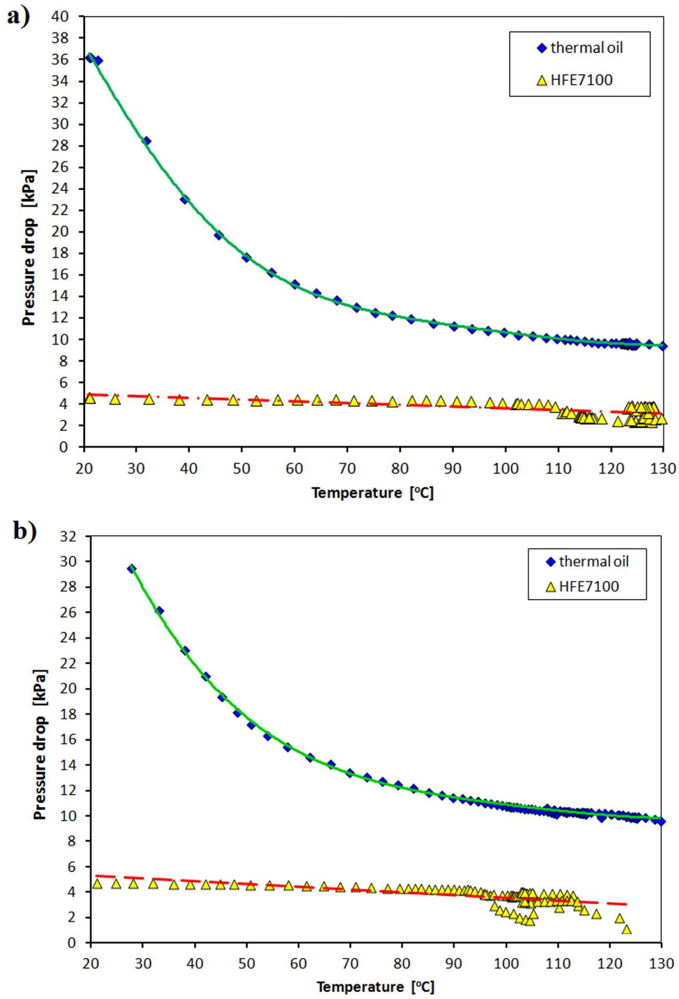

Figure 7: Pressure drop vs. temperature of the thermal oil and HFE7100 in the evaporator – ORC system operation: a) with regeneration, b) without regeneration.

long. A change in density of the thermal oil in the temperature range of 20 to 130 °C was small (it decreased from 863 kg/m^3 to 792 kg/m^3) and had no greater influence on the pressure drop value. In the case of HFE7100 medium, a drop in pressure has been no more than 5 kPa independently of the temperature and the operation mode (with/without regeneration). A small pressure drop in the flow of the low-boiling medium was due to a low working medium viscosity and its small change in relation to the thermal oil. Within the temperature range 20–130°C, the

HFE7100 viscosity decreased from 0.66 mPa s to 0.13 mPa s. Additionally, during the startup of the cogeneration system the HFE7100 medium has a liquid form, and only in the evaporator it takes the form of a superheated vapour, the degree of dryness of which is usually higher than 1 ($x > 1$). During the medium state change, there is a large drop in density of the working medium in the temperature range 20–130 °C, i.e., from 1550 kg/m^3 (liquid form) to 7.05 kg/m^3 (vapour form) – meaning that the second value is more than 219 times lower than the first one. Despite substantial changes of HFE7100 density, no significant pressure drops in the evaporator were observed. Summing up, we can say that the working medium viscosity is what determines a pressure drop, not the working medium density. This is worth bearing in mind when selecting components of an ORC cogeneration system. Figure 8 provides the representation of the pressure drop curve (in the regenerator) as a function of HFE7100 temperature at both the vapour as well as the liquid side.

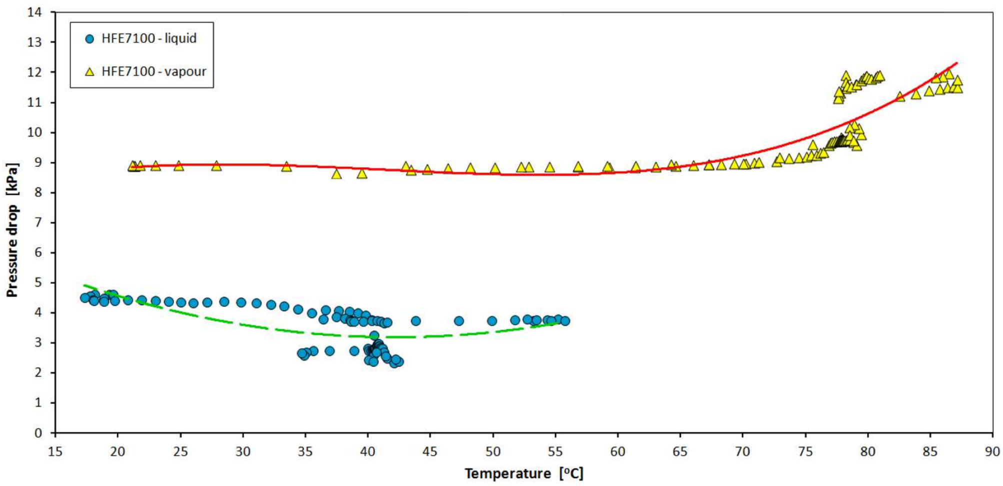

Figure 8: Pressure drop in the regenerator vs. HFE7100 temperature, at both liquid and vapour sides.

For the purposes of determining the trend line values for pressure drop in the regenerator during the flow of a low-boiling medium HFE7100, the polynomial regression was applied (i.e., the polynomial function of degree 4 – continuous line) for a vapour form and a polynomial function of degree 2 was used for a liquid form (broken line). For the vapour temperature range from 20 °C to 60 °C the pressure drop in the regenerator remained constant (about 8.8 kPa). After exceeding the temperature of 60 °C, an increase of pressure drop has been observed, which was about 12.7 kPa at a temperature of about 88 °C. However, a pressure drop was noted with an increase of temperature at the liquid side. The maximum pressure drop value measured at the regenerator outlet was approx. 4.7 kPa and it occurred at a temperature of 17 °C, while the minimum pressure drop value was approx. 2.3 kPa at about 42 °C. The regenerator is a shell-and-tube heat exchanger, it was installed vertically in the ORC installation. A liquid working medium flows from the bottom to the top in the pipes and a vapour working medium flows from the top to the bottom in the shell. Thus, the two mediums flow through alternate channels, always in counter current flow. During the heating phase of the heat exchanger, the condensation of the medium could take place, resulting in a higher flow resistance of the vapour.

Figures 9a and 9b provide the plots of pressure drop (in the condenser) as a function of temperature (glycol and HFE7100) for the ORC installation operating with or without regeneration, respectively. For the purposes of determining the trend line values for pressure drop in the condenser (in the ORC cycle with regeneration) during the flow of a low-boiling medium HFE7100, the polynomial regression was applied (the polynomial function of degree 2). In the case of the glycol flow (Fig. 9a) for the temperature range 17–30 °C a linear regression was used and for the temperature range 30–74 °C the polynomial regression was applied (the polynomial function of degree 4). A linear decrease in pressure occurred up to a temperature of about 30 °C – only during the startup and heating-up phases – and decreased nonlinearly with the increase of the working mediums' temperatures up to 74 °C, which was due to the drop in glycol viscosity. In the ORC operation mode with regeneration, the pressure drop in the condenser decreased as the glycol temperature increased. The maximum pressure drop value (3.7 kPa) was observed at the glycol temperature of 18 °C. The pressure drop increased in line with HFE7100 temperature, with a maximum increase by about 0.35 kPa at 69 °C. In the case of the ORC thermal cycle without regeneration, the linear regression was used for the two temperature ranges, namely 15–65 °C and 65–70 °C, in order to determine the trend line values for pressure drop during the glycol flow. The first temperature range concerns the heating process of the ORC cogeneration system.

In the case of cycle operation mode without regeneration, the pressure drop decreased slightly (and was in the range 0.59–0.67 kPa) with an increase in glycol temperature from 14 °C to 66 °C. After exceeding the temperature of 66 °C, an almost two fold increase in pressure drop has been noted, with a maximum value of 1.3 kPa at approx. 70 °C. For the purposes of determining the trend line values for pressure drop in the condenser during the flow of the working medium in the

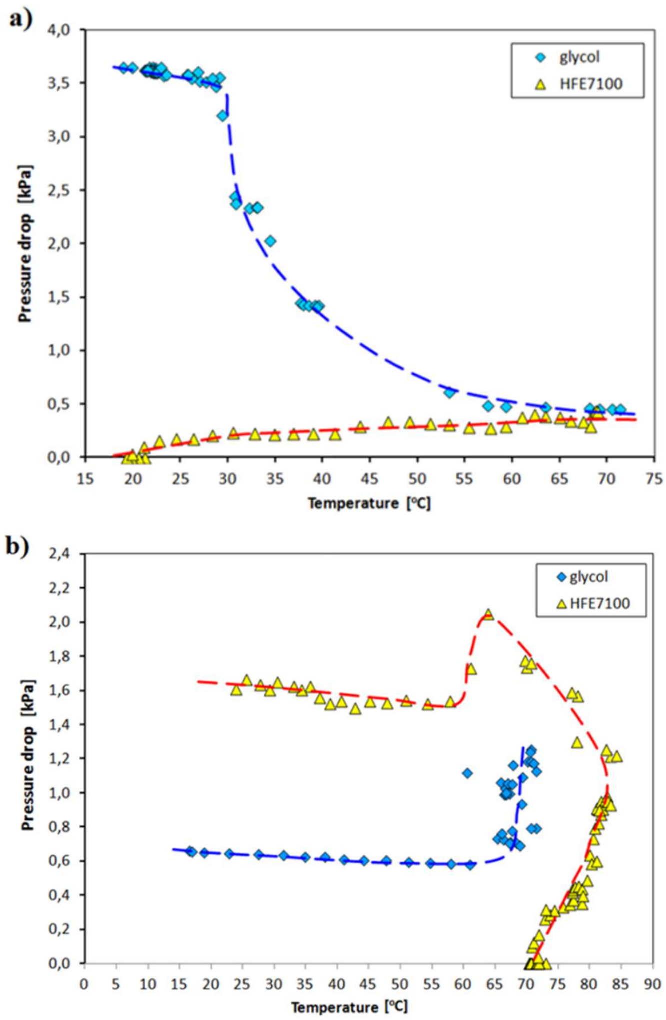

Figure 9: Pressure drop in the condenser vs. glycol/HFE7100 temperature, during ORC system operation mode: a) with regeneration, b) without regeneration.

temperature range up to 61 °C, the linear regression was applied. In terms of the temperature range 61–85 °C, the polynomial regression was used (the polynomial function of degree 6). During the heating-up phase of the ORC installation, a linear decrease in pressure for the HFE7100 flow was noted. Increasing drop in glycol pressure was caused by higher pressure drop of the working medium which, after exceeding the temperature of 61 °C, began to evaporate resulting in a momentary condenser malfunction. The maximum pressure drop relating to HFE7100 flow was about 2.1 kPa and occurred at 61 °C. During normal operation of the installation, i.e., after the heating-up phase, the working medium's temperatures ranged from 70 °C to 85 °C and the pressure drops varied in the range of 0.025 to 1.1 kPa. Apart from working medium flow rate, an essential feature inherent in pump is net delivery head. The net pump delivery head was calculated in accordance with the following formula:

$$H_U = \frac{u_t^2 - u_s^2}{2g} + \frac{p_t - p_s}{\gamma} + h \; . \tag{1}$$

Net delivery head values measured for the peripheral pump operating in the ORC system with and without regeneration of the working fluid are presented in Figs. 10a and 10b, respectively.

The determination of the pump's head and the characteristics as a function of time enables to determine the time needed for the warming of the installation which depends on the temperature, pressure and flow rate of the working medium. The research on the peripheral pump operating in the ORC system with and without regeneration involved the gradual increase of the pressure, maintaining constant operating parameters of the installation and performing measurements in the steady state. The definition of steady state was introduced. Steady state denotes the state in which the flow rate change of the media (thermal oil, working medium HFE 7100 and 40% solution of ethylene glycol in water) does not exceed 1% of the maximum flow rate for 5 min. The acceptable maximal (1%) flow rates are: for the thermal oil – 0.004 kg/s, for the working medium (HFE 7100) – 0.002 kg/s and for the glycol solution – 0.005 kg/s. Additionally, the pressure in the steady state should not exceed 12 kPa (i.e., 1% of the maximum pressure value) for 5 min and the changes in temperature values should not exceed 1 °C. Thus, the steady state is when the values of pressure and flow rate change do not exceed 1% of the maximum pressure/flow rate value in 5 min, and the temperature values are stable (±1 °C). The maximum net delivery head was approximately 43 m for the pump operating in the regenerative ORC system, and approx. 41 m in the nonregenerative cycle. In the first operation mode (i.e., regenerative cycle), a higher delivery head was achieved due to lower flow resistance in the regenerator compared to the by-pass pipeline in the nonregenerative cycle. The increased flow resistance in the by-pass pipeline was caused by a flow regulating valve and fittings (i.e., elbows, tees). The delivery head gives the information about the pressure created on the delivery side of the pump (at the discharge port). In order to calculate pump discharge pressure, one can use the following formula

$$N_U = \rho \, g \, H_U \; . \tag{2}$$

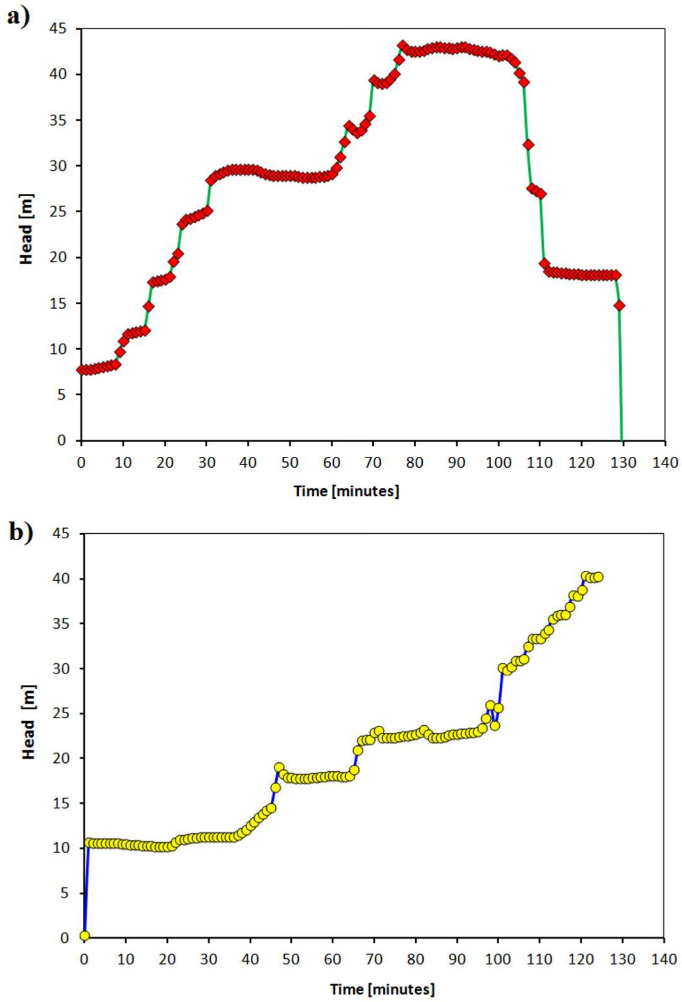

Figure 10: Net pump delivery head vs. time, measured during ORC system operation mode: a) with regeneration, b) without regeneration.

The pressure values of the working medium, which amounted to 0.61 MPa for a delivery head of 43 m and 0.59 MPa for a delivery head of 41 m, were calculated from Eq. (1). It was concluded that the examined pump fails to deliver the recommended pressure for optimal performance which will result in a reduced electric power output of the ORC cogeneration system. Nevertheless, the experimental investigation identified the actual performance parameters of the ORC system and made it possible to determine thermal and flow characteristics of individual installation elements such as heat exchangers, control valves or the piping.

The effective power of the pump means the net power used to increase the fluid energy. The net pump power was determined using the following formula:

$$P_U = \rho\, g\, q_V\, H_U \;. \tag{3}$$

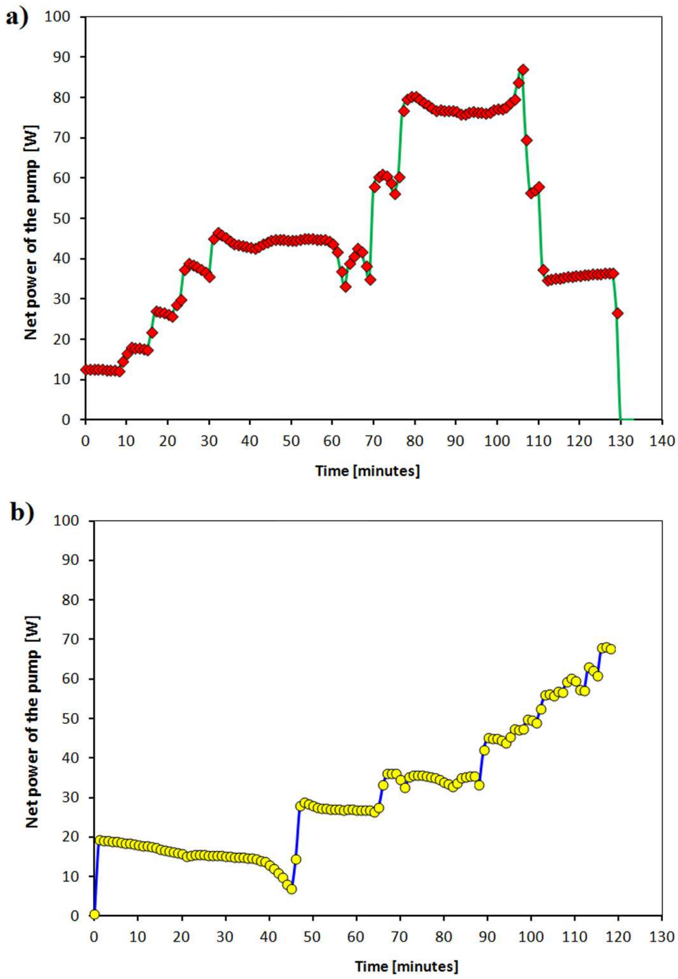

Figure 11: Net power of the peripheral pump vs. time, during ORC system operation mode: a) with regeneration, b) without regeneration.

Figures 11a and 11b present the values of the net pump power as a function of time, measured during ORC system operation with and without regeneration, respectively. It was noticed that the maximum net pump power was about 88 W in the regenerative ORC system and about 70 W in the nonregenerative system. The effective power obtained for the regenerative Rankine cycle was about 25% higher than that seen with the nonregenerative cycle. This is based on the fact that the working medium has to be lifted to the regenerator height (i.e., about 1.4 m along with connections).

Figure 12 shows the HFE7100 temperature as a function of absolute pressure. These values were measured before the expansion valve (simulating operation of an expansion device) in the ORC system with and without regeneration.

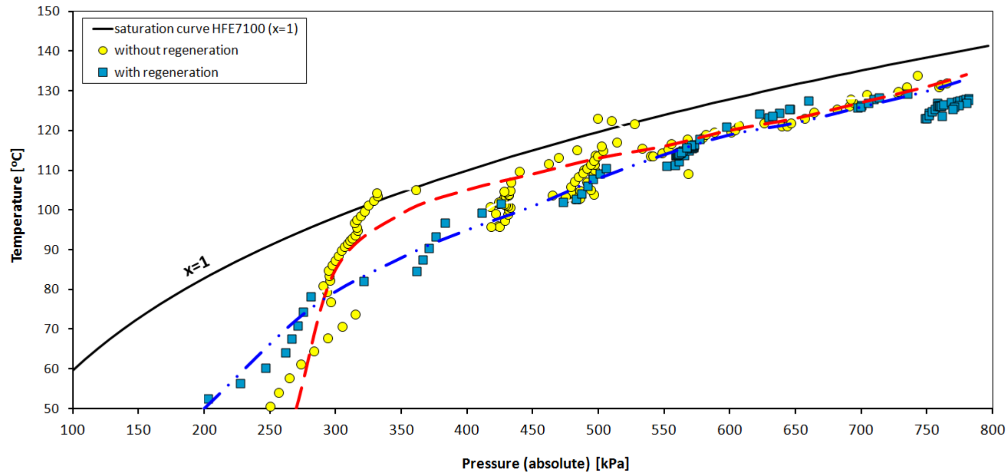

Figure 12: Temperature vs. absolute pressure for HFE7100.

It was determined that a minor superheating occurred only where the cycle has operated in the nonregenerative mode within pressure ranges: 310–360 kPa and 480–520 kPa. In the other pressure ranges the working medium's pressure was below the saturation curve (marked by $x = 1$). Volumetric expansion machines are capable of running within the wet vapour area [9], i.e., with a slightly increased damp of the working medium. However, turbine expanders are susceptible to medium damp and require a suitable level of overheating degree ($x > 1$) in order to operate properly. An adequate overheating degree of the working medium vapour can be ensured, firstly, by reduction of the vapour pressure while maintaining constant flow rate and temperature, secondly, by increase in the temperature of the medium while keeping constant pressure and flow rate, and thirdly, by reduction of the medium's flow rate at constant pressure and temperature. However, there must be adequate temperature, pressure and flow rate to provide minimum operating parameters of the expansion device. Summing up, the examined pump does not provide an appropriate overheating degree of the working medium and thus cannot be applied to an ORC cogeneration cycle with a vapour turbine.

Peripheral pumps are usually available in single-stage or two-stage models, the maximum efficiency of which is in the range 35–52% [19]. The heat being generated by a running pump is transferred to the working medium and transmitted to the environment by natural convection. The amount of heat transferred to pump's working medium can be calculated by applying the following formula:

$$Q = m\, c_p\, (t_t - t_s) \ . \tag{4}$$

The thermal power output of the pump presented as a function of time during the ORC system operation with and without regeneration is shown in Figs. 13a and 13b, respectively.

Estimation of the pump's thermal energy exported to the working medium is very important since the medium is heated excessively if heat losses are high. If the temperature of the pump casing goes too high then it may cause evaporation of the working medium, resulting in cavitation. It may damage the pump and contribute to a malfunctioning ORC cogeneration system. It is necessary, therefore, to monitor pressure and temperature of the working medium inside the pump, particularly in the suction channel, where there is the lowest pressure in the low-boiling medium's cycle. The occurrence of cavitation in the pump results in turbulences and fluctuations of the working medium flow and may cause incorrect operation of the overall system. The thermal power output of the pump operating in the regenerative cycle was in the range 340–590 W, while in the nonregenerative cycle it was from 380 W to 595 W. It was determined that the average calculation error of the pump's thermal power output was approx. ± 25 W with the accuracy of $\pm 0.1\,^{\circ}$C of the measured liquid temperature value. It is important to point out that the error value depends on the temperature value which affects both specific heat and viscosity of the liquid. Assuming that there are no heat losses to the pump's immediate surroundings, the estimated maximum efficiency of the pump does not exceed 44% or 37% for the regenerative or nonregenerative cycle, respectively.

4 Summary and conclusions

On the basis of measurement carried out, the pressure drops in the heat exchangers incorporated into the ORC installation (i.e., evaporator, condenser and regenerator) were determined at varying working mediums' temperatures. In the

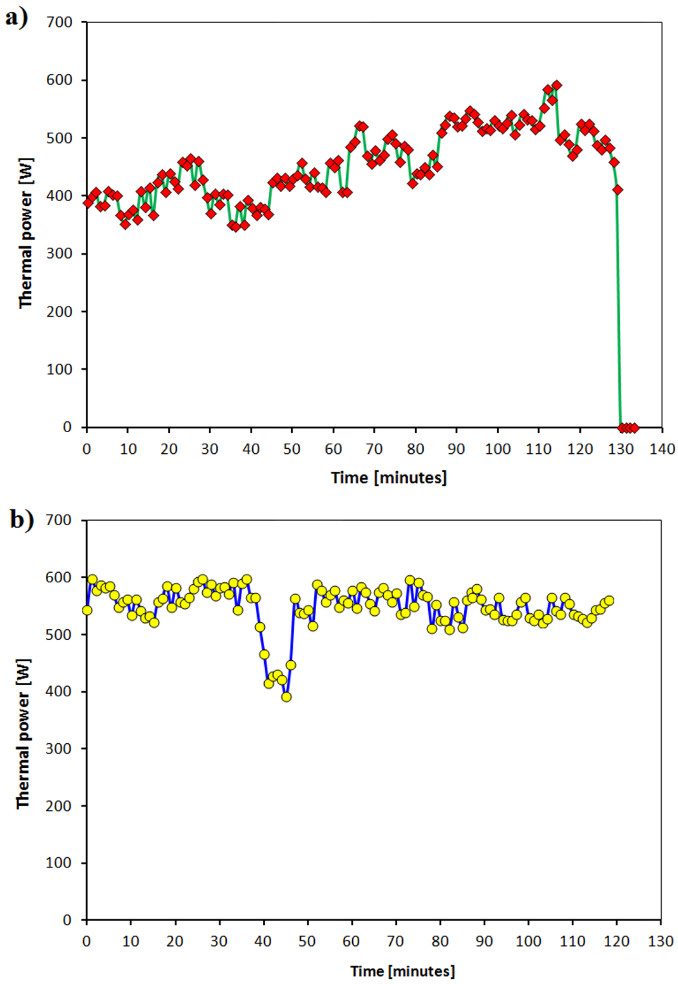

Figure 13: Thermal power output of the pump vs. time, during ORC system operation mode: a) with regeneration, b) without regeneration.

regenerative and nonregenerative cycle on the thermal oil side, the maximum pressure drop was 36 kPa and 30 kPa, respectively. However, the pressure drop on the HFE7100 side was almost constant — irrespective of the type of cycle — at about 5 kPa. The maximum pressure drop in the regenerator was about 12.7 kPa on the vapour side and about 4.7 kPa on the liquid side. As for the glycol flow in the condenser, the maximum pressure drop was 3.7 kPa or 1.3 kPa, depending on whether this was a regenerative or nonregenerative cycle. The maximum pressure drops measured for the HFE7100 flow in the condenser were 0.35 kPa and 2.1 kPa in the cycle with and without regeneration, respectively.

The maximum value of the net pump delivery head was approximately 43 m in the case where the pump was operating in the regenerative organic Rankine cycle and approx. 41 m in the nonregenerative cycle. It was established that the maximum net power of the pump operating in the ORC system with regeneration was about 88 W and in the case without regeneration it reached 70 W. It was concluded that the examined pump (PK70) fails to deliver an optimal pressure for the tested working medium, which will result in the lower than expected electric power output of the ORC cogeneration system.

The thermal power output of the pump operating in the cycle with regeneration was in the range 340–590 W, while in the cycle without regeneration it remained within the range from 380 to 595 W. Under the assumption that there are no heat losses to the pump's immediate surroundings, assessed the maximum efficiencies of the pump operating in the regenerative and nonregenerative cycle, which amounted to 44% and 37%, respectively.

Peripheral pumps are characterized by low flow rate and high discharge pressure. However, in the case of PK70 pump, the pressure achieved at the discharge port was too low (i.e., below 1 MPa), which was probably caused by a low viscosity and a high density of the HFE7100 in relation to water. The pump provides the required flow rate of the working medium, i.e., 0.16–0.17 kg/s, but HFE7100 vapour was within the wet area ($x < 1$) in Fig. 12 chart, and it is therefore not possible to use a turbine expander in the ORC cogeneration cycle. It follows from the above that a PK70 pump is not suitable for use with an ORC system, since it does not to meet all the criteria necessary for the proper operation of a turbine expander as a device for expanding the vapour to generate power.

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