EXPERIMENTAL INVESTIGATION ON THE EFFECT OF A SEPARATOR ON OPERATING PARAMETERS OF AN ORC

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ABSTRACT

The paper presents the results of the experimental investigation on the effect of a vapour-liquid separator used for a low-boiling medium on operating parameters of an organic Rankine cycle (ORC). A biomass boiler with thermal power of 25 kWt was used as a heat source. Pellets were used as its fuel. In the ORC system, the working medium (HFE7100) was heated with thermal oil. Expansion of the low-boiling medium took place in a four-stage radial-flow microturbine, whose rated electric power and rotational speed are respectively 2.5 kWe and 24 krpm. It is important that the operation of this microturbine is both stable and failure-free. For this, an appropriate vapour overheating degree is needed at the microturbine's supply side. Therefore, a prototypical inert vapour-liquid separator for the working medium was designed and built. This device allows for two modes of operation for the system; bypass mode and turbine mode. The effect of the vapour-liquid separator on the operating parameters was described and shown using heat and flow characteristics. Those characteristics were prepared on the basis of measurements conducted with thermodynamic flow meters. Observing the process was possible by using a specifically designed sight vane. It was observed that the tested separator worked as heat storage in the ORC installation. Both during transition states of the microturbine and instantaneous fluctuations in the thermal power of the boiler (stemming from its thermal inertia and the cyclical feeding of fuel), the separator provided stable operating conditions at the proper overheating degree of the working medium's vapour. It was found that in vapour-fed systems such a separator can also work as a clarifier or a filter for solid particles.

1. INTRODUCTION

Low-temperature waste heat, available in the temperature range from 120°C to 650°C, corresponds to about 50% of the total energy used in all industrial branches. Meanwhile, it could be utilised to produce electrical energy (Pethurajan *et al.*, 2018, Park *et al.,* 2018). Thermal energy from the sources of waste heat can be converted into electrical energy using CHP (Combined Heat and Power) systems, including ORC systems in which organic low-boiling mediums are usually used (Martinez *et al.*, 2017). To ensure the proper operation of an expansion machine, for example, a turbine (Ziółkowski *et al.*, 2014), s scroll expander (Kaczmarczyk *et al.*, 2015), a screw expander (Dumont *et al.*, 2017) or a vane expander (Rak *et al.* 2018), the parameters of the medium that feeds this expansion machine should have appropriate values. The medium's vapour should be superheated and have a suitable flow rate, pressure and temperature. For this reason, carefully selected vapour-liquid separators are used. In cogeneration systems, a separator is mounted at the turbine's supply side in order to protect the flow system against erosion (Du *et al.*, 2019, Kaczmarczyk *et al.*, 2017). It should be noted that separators are often used in geothermal systems with turbines (Zarrouka and Purnanto, 2015; Valdimarsson, 2011) as well as in ORC systems (Xu *et al.*, 2019). In the properly designed separator, heat losses and pressure drops are small and can, therefore, be neglected in energy analyses (Pethurajan *et al.*, 2018, Li *et al.*, 2012).

In cogeneration systems with volumetric expanders, lubricants are often used to ensure the proper operation of expansion machines (Dumont *et al.*, 2018), what is connected with the risk that oil can get to the working medium. Leaks of oil (which serves as a lubricant for the expander) to the working medium cause that the circulation pump consumes less electric energy, while also reducing the shaft's power and electric power produced by the expander. It was found that the more oil is in the working medium the lower are the values of the heat penetration coefficients in the heat exchangers and the efficiency of the entire ORC system drops (Feng *et al.*, 2019). As far as oil-lubricated expansion machines are concerned, separators are mounted at their outlet (Zanelli and Favrat, 1994). Oil-free expansion machines with gas bearings lubricated with the working medium allow for the use of a hermetically-sealed construction and this helps to reduce their vibration and noise levels (Kaczmarczyk *et al.*, 2016). To ensure constant operating parameters of the ORC system at the supply side of expansion machines, heat storages are mounted, which additionally cause an increase in the overall efficiency of the thermodynamic cycle and a financial benefit (Roskosch and Atakan, 2017; Pantaleo *et al.*, 2017; Chen *et al.*, 2018). This paper presents the results of experimental research on an ORC system with a microturbine and a vapour-liquid separator for the low-boiling working medium. It was determined that the separator enables obtaining the proper superheating degree of the working medium, and this ensures stable operation of the ORC system during transient states due to an accumulation of heat energy.

2. TEST RIG

The test rig consists of three main cycles, namely, the heating cycle, the working medium's cycle and the cooling cycle. Its simplified scheme is shown in Fig. 1. In the heating cycle, a multi-fuel boiler, whose power is 25 kW_t, was used as a heat source and was fired with wood pellets. The working medium (HFE7100) was heated using thermal oil, and the evaporation process took place in an evaporator (plate heat exchanger). An inverter was applied to regulate the flow rate of the thermal oil. In the working medium's cycle, a regenerative shell-and-tube heat exchanger and a plate heat exchanger (as a condenser) were used. A vapour-liquid separator for the working medium's vapour was mounted before the microturbine inlet. The pump's inverter served to regulate the flow rate of the HFE7100 medium. In the working medium's cycle, a prototypical four-stage radial-flow microturbine was used as an expansion machine. The microturbine features hermetically sealed design; inside the casing, the generator and the blade system are mounted on the same shaft. The microturbine's shaft is supported on gas bearings lubricated with the working medium.

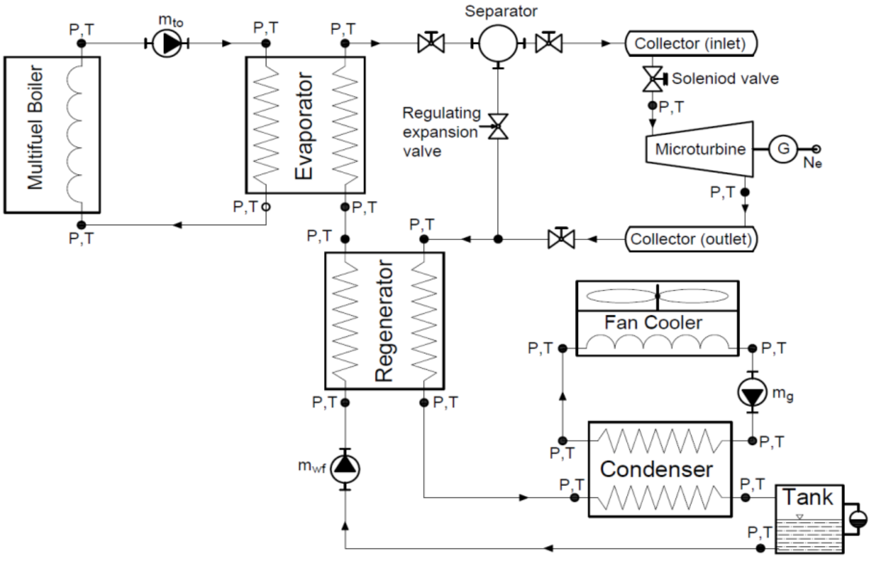

Figure 1: Simplified scheme of the test rig

The microturbine is coupled with a three-phase synchronous generator with permanent magnets. At the nominal rotational speed of 24,000 rpm, the microturbine is capable of producing 2.5 kilowatts of electrical energy. An AC/DC converter (rectifier) was used to convert alternating current (AC) to direct current (DC). The produced energy was consumed by heaters and DC bulbs. In the cooling cycle, the heat was dissipated using a cooling tower and the flow rate of the ethylene glycol solution was regulated by the pump's inverter.

2.1 Separator design

The designed inert separator was built using pipes made from stainless steel. A 3D model of the separator and its dimensions are shown in Fig. 2.

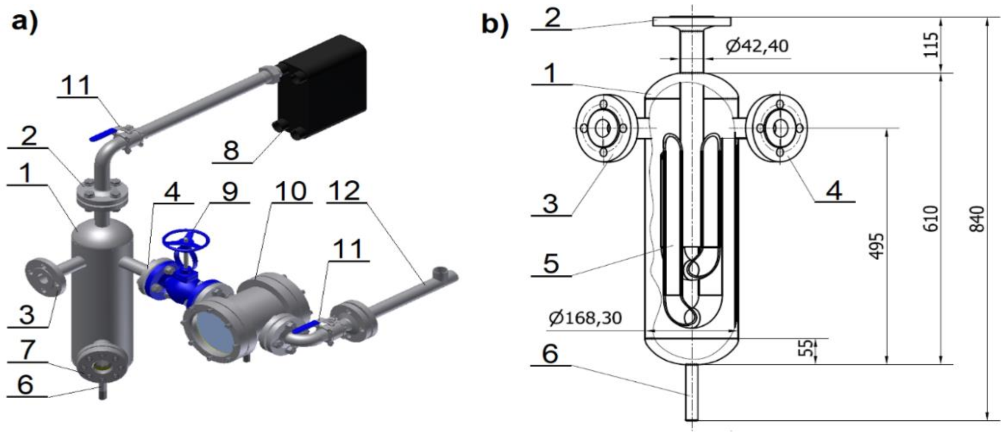

Figure 2: The 3D model (a) and scheme (b) of the separator; 1 – casing, 2 – supply flange, 3 – separator outlet for feeding the microturbine, 4 – by-pass connector, 5 – U-tubes of the separator, 6 – stub pipe, 7 – separator's peephole, 8 – evaporator, 9 – flow regulating valve, 10 – main peephole, 11 – ball valve, 12 – pipe that feeds the regenerator

The separator was connected with the evaporator outlet (8) using flange (2); moreover, it was connected with the microturbine's collecting pipe using a flange (3). During the start-up and heating process of the ORC installation, the working medium's wet vapour was directed to the U-tubes of the separator (5) and then (using the by-pass pipe) to the pipeline (12) that feeds the regenerator. The main peephole (10) served for monitoring the flow of the working medium's vapour. After the vapour was superheated, it was directed to the microturbine. The peephole (7) was used to monitor the condensate level in the separator. The condensate was released from the separator (1) was done using the stub tube (6). During the microturbine's start-up, the flow of the working medium through the pipelines (the by-pass pipe and the pipe that feeds the microturbine) was regulated using the valve mounted at the evaporator outlet (8). The ball valve (11) was used when there was a need to disconnect the separator from the ORC installation. The photos of the ORC installation (with and without the separator) are shown in Fig. 3.

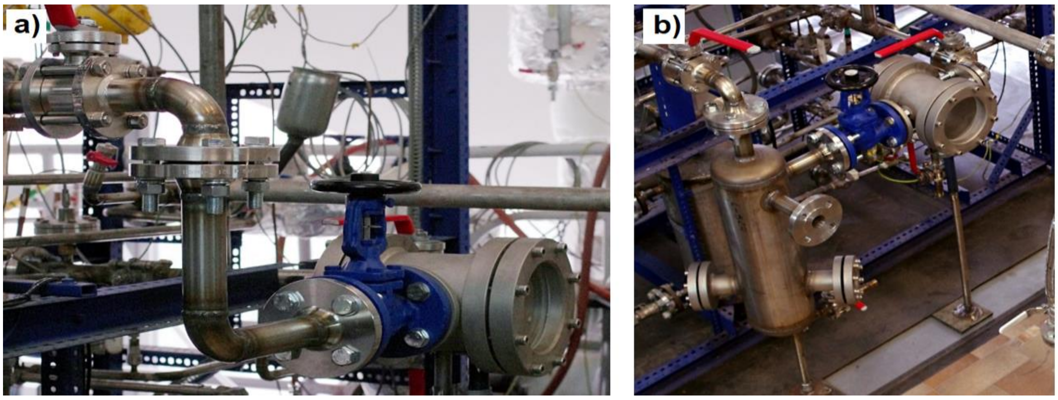

Figure 3: Photo of the test rig: a) with no separator, b) with the separator

The separator (without the thermal insulation) weighs 30 kg and its volume is 10.75 dm^3. In order to assess the influence of the separator on the operation of the ORC installation, at first, the measurements were carried out for the system without the separator (i.e. using the by-pass pipe shown in Fig. 3a) and then with the separator (Fig. 3b). It is worth noting that during the measurements, both the by-pass pipe and the separator had thermal insulations, 40 mm thick. The characteristics of the materials used to build the separator are listed in Table 1.

Table 1: Characteristics of the materials that were used to manufacture the separator

Material	Thermal conductivity (λ)	Specific heat (C)	Density (ρ)	Mass (M)
stainless steel 316L	15 W/m K	500 J/kg K	8,000 kg/m^3	30.0 kg
mineral wool	0.038 W/m K	1,030 J/kg K	175 kg/m^3	3.5 kg

The total volumetric heat capacity of the separator (Q_c) is equal to the sum of the volumetric heat capacities of the constructional materials and the volumetric heat capacity of the working medium. It can be calculated using the following formula:

$$Q_c = Q_{ss} + Q_{mw} + Q_{wf} \tag{1}$$

where: Q_{ss} – heat capacity of the stainless steel, Q_{mw} – heat capacity of mineral wool, Q_{wf} – heat capacity of the working medium.

The summands in equation (1) can be calculated using the following formulas:

$$Q_{ss} = C_{ss} \cdot \rho_{ss} \tag{2}$$

$$Q_{mw} = C_{mw} \cdot \rho_{mw} \tag{3}$$

$$Q_{wf} = C_{wf} \cdot \rho_{wf} \tag{4}$$

Using equations (2-4), the volumetric heat capacity of the steel construction, of the mineral wool and of the working medium were calculated and are, respectively, equal to 4,000 kJ/m^3 K, 180.25 kJ/m^3 K and 1.75 kJ/m^3 K. It means that the volumetric heat capacity of the separator's construction is much higher than the volumetric heat capacity of the working medium located inside this construction. Furthermore, the accumulated heat can be transferred to the working medium during a temporary shortage of heat or fluctuations in the values of the operating parameters of the ORC system. The occurrence of the nonstationary states during the operation of the ORC system stems from the cyclic operation of the screw-conveyor feeder that was used to feed the multi-fuel boiler with pellets; it can also be caused by the way in which the regulation of the flow rate of the working medium that fed the microturbine was realised. During the operation of the microturbine under nominal conditions, the parameters of the working medium were as follows: flow rate – 0.17 kg/s, absolute pressure at the supply side – 1,270 kPa, temperature – 165°C. During the cyclic operation of the screw-conveyor feeder, which mated with the boiler, it was noted that the maximal fluctuations of the temperature of the working medium (ΔT) were in the range from 10 K to 15 K. It means that the thermal power of the working medium was not constant, which caused that the operation of the microturbine was not stable. The change in the thermal power due to temperature fluctuations of the working medium can be calculated using the following equation:

$$N_t = m_{wf} \cdot C_{wf} \cdot \Delta T \tag{5}$$

where: ΔT – temperature difference of the working medium.

Changes in the temperature of the working medium (in the range of 10–15 K) during nominal operation of the ORC system caused fluctuations of the thermal power (from 2.16 kW$_t$ to 3.23 kW$_t$), which corresponds to, respectively, 8.64% and 12.92% of the rated power of the multi-fuel boiler.

3. RESULTS OF THE EXPERIMENTAL RESEARCH

As it was mentioned before, appropriate parameters of the working medium should be provided for the proper operation of the microturbine. One of these parameters is the superheating degree of the working medium that feeds the microturbine. If the superheating degree of the working medium is adequate (in other words, the operation is above the saturation line, $x>1$), the microturbine's blades are protected against erosion as there are no liquid droplets in the working medium's vapour. Moreover, if the working medium's vapour is wet (i.e. when $0<x<1$), the microturbine's gas bearings cannot operate properly and it could lead to their damage and thus a failure of the microturbine or of the ORC system. Therefore, the vapour-liquid separator for the working medium's vapour was mounted at the microturbine's supply side in the ORC system. The exemplary results of the research on the ORC system with the separator are presented in Fig. 4.

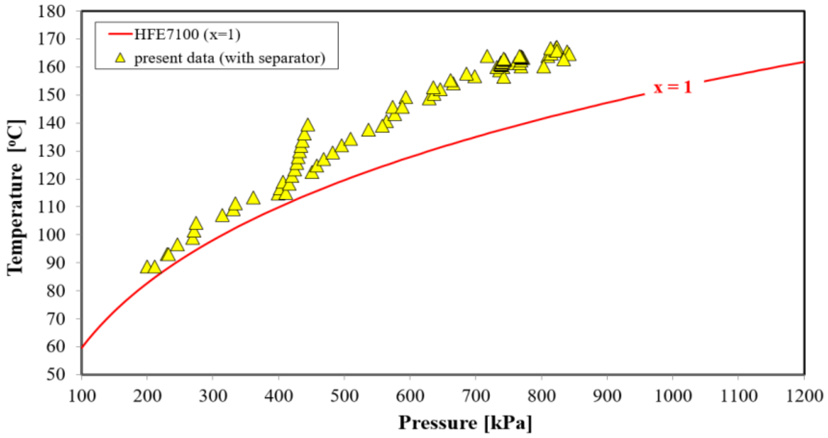

Figure 4: Temperature of the working medium (HFE7100) versus its pressure, measured during operation of the ORC with the separator

When looking at Fig. 4, one can see that all measured values are located above the saturation line of the HFE7100 medium ($x>1$), which means that the working medium's vapour at the microturbine's supply side was superheated.

As far as the operation of the ORC system with no separator is concerned, it was observed that not all measured values were situated above the saturation line (Fig. 5); many of them show that the vapour that fed the microturbine was wet.

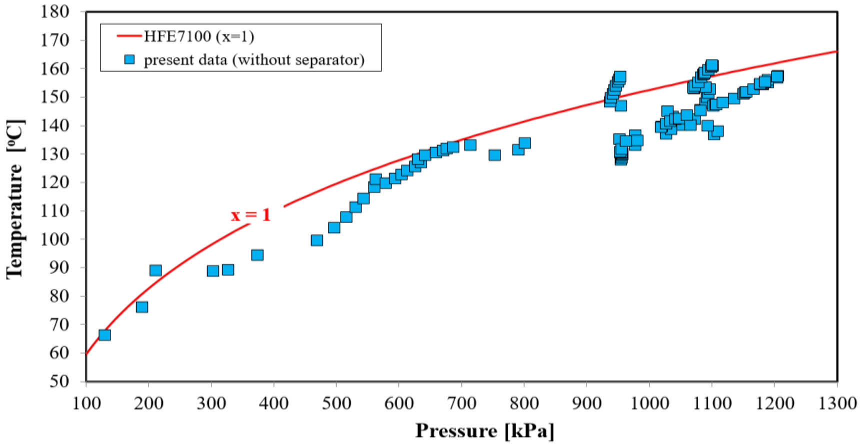

Figure 5: Temperature of the working medium (HFE7100) versus its pressure, measured during operation of the ORC system with no separator

If the microturbine is fed by wet vapour, the rotor is not able to operate properly and also the gas bearings cannot operate properly (as they are fed with the vapour that contains liquid droplets). In such an event, the microturbine's rotor disk also has to operate with the wet vapour. In order to guarantee the failure-free operation of ORC cogeneration systems that mate with fluid-flow machines, the superheating of the working medium should be at least 5°C under the fixed operating conditions.

However, in the engineering practice, the superheating of the working medium is usually higher due to occurring transient states and heating the system during the start-up phase, which may cause supercooling of the medium.

Figure 6 presents the superheating temperature of the HFE7100 medium versus pressure, measured during the operation of the ORC system with the separator. The superheating temperature was low when the pressure was low; nonetheless, the temperature increased as the pressure increased. For example, the superheating temperature was in the range from 5°C to 8°C at the pressure of 200 kPa and in the range from 19°C to 23°C at the pressure of 850 kPa. Because in the first stage of the operation the ORC installation and the microturbine were heated, the superheating temperature was lower.

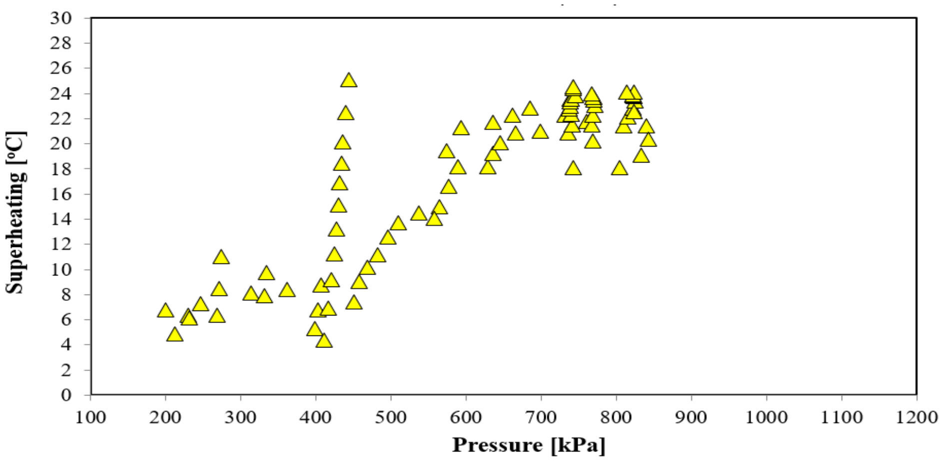

Figure 6: Superheating temperature of the working medium (HFE7100), measured in the ORC system during its operation with the separator

The superheating temperature of the HFE7100 medium versus the pressure at the microturbine's supply side, measured during the operation of the ORC system with no separator, is presented in Fig. 7.

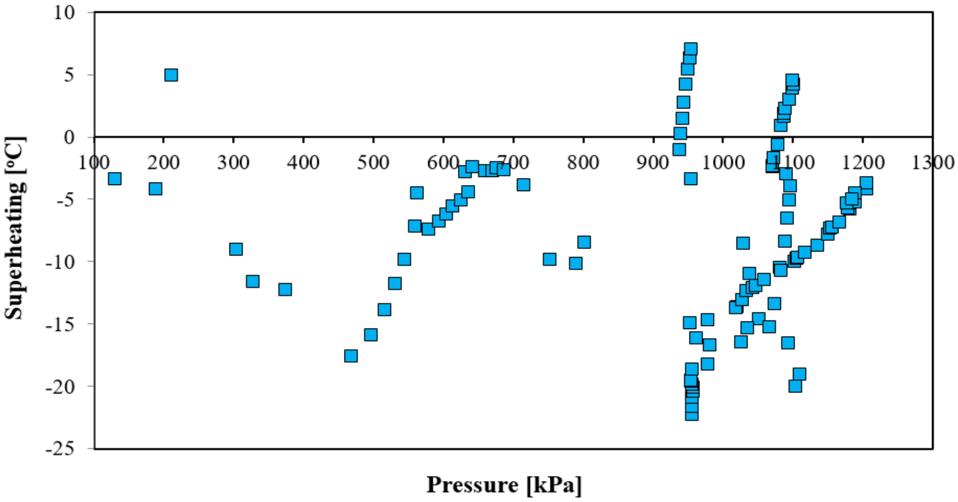

Figure 7: Superheating temperature of the working medium (HFE7100), measured in the ORC system during its operation with no separator

Having analysed Fig. 7, we see that the superheating temperature was in the range from -22°C to 7°C whereas the pressure was in the range from 120 kPa to 1,200 kPa. The fluctuations of the thermal power, resulting from the cyclic operation of the feeder and the boiler and also from the heating process of the installation, caused changes in the temperature of the thermal oil, which directly translated into superheating of the working medium. In the system equipped with the separator, temporary drops in the temperature of the oil were compensated by thermal energy accumulated by the separator, thereby ensuring the proper superheating of the working medium. The separator enabled separation of the liquid droplets from the vapour, and then heating and superheating of the medium using heat accumulated within. If the microturbine has to operate with wet vapour, it causes fording of the blade system and a decrease in the rotational speed of the microturbine, with increasing vibration and noise levels. A decrease in the rotational speed of the microturbine causes that it produces less electrical energy and there is also a decrease in the efficiency of the microturbine and of the ORC system. For example, it was determined that in the ORC system with no separator, the maximum thermal efficiency of the cycle was 1.82% and it was achieved at the maximum power (473 W_{el}) when the microturbine had a rotational speed of 14,340 rpm. However, in the ORC system with the separator, the efficiency of the cycle was 6.02% and the power and rotational speed of the microturbine were respectively 1,487 W_{el} and 18,540 rpm. It should be noted that in the case discussed herein solid particles that appeared due to wear of the components of the installation (e.g. the gear pump) deposited themselves inside the separator. Small solid particles getting inside the gas bearings, can cause their malfunctioning as a result of clogging, which can also lead to their damage.

4. CONCLUSIONS

The article discusses the results of experimental research on the ORC system, measured during its operation both with and without a vapour-liquid separator. The separator was used for the vapour of the low-boiling medium (HFE7100). It was found that the separator can enable appropriate superheating of the working medium to feed the microturbine. When there was no separator, the ORC system operated under the wet vapour conditions, which resulted in a decrease in the efficiency of the system and of the microturbine. It was shown that the designed separator can not only separate droplets from the working medium's vapour but can also serve as a thermal energy storage device, ensuring stable operation of the microturbine and the entire ORC system.

NOMENCLATURE

C	specific heat	(J/kg K)
m	mass flow rate	(kg/s)
M	mass	(kg)
N	power	(W)
P	pressure	(Pa)
T	temperature	(K)
ΔT	temperature difference	(K)
Q	volumetric heat capacity	(J/m^3 K)
λ	thermal conductivity	(W/m K)
ρ	density	(kg/m^3)
x	quality	(-)

Subscript

c	total
el	electrical
g	40% solution of ethylene glycol
mw	mineral wool
ss	stainless steel
t	thermal
to	thermal oil
wf	working fluid

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