THE ANALYSIS ON POWERING THE ORC (ORGANIC RANKINE CYCLE) SYSTEM BY HEAT STORAGE DEVICE

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ABSTRACT

Some of the heat sources, such as e.g. waste or solar, are featuring floating thermal and output characteristics. Heat recovery from such sources is difficult while the changes in the heat source output and heat carrier temperature negatively influences the continuity and operational conditions of energy conversion systems and devices. Especially vapour power plants, such as ORCs, should utilize the heat sources having steady thermal and output characteristics. The heat source floating characteristics can be stabilized using the heat storage devices providing the thermal energy accumulation at stable output and temperature level. Heat storage device can be adopted as a steady-level heat source for ORC system. In this paper the results of the experiments carried on the ORC system powering from heat storage system, which were carried out on a prototype ORC test-stand are presented. The results showed that adopting the heat storage devices for powering the ORC systems is a promising way of utilizing the floating waste and solar heat sources.

1. INTRODUCTION

Selected renewable and waste heat sources applied for powering ORC systems are appearing periodically and are featuring floating characteristics (including heat source power, heat carrying medium output and temperature) and low-quality. Therefore, ORC systems have to adapt to changing conditions of the heat supply which causes the difficulties in their designing. The thermal properties (pressure and temperature) of vapour which is obtained in evaporator may vary which directly translates to floating operating conditions of the expander. This operating conditions may be disadvantageous if expander lifetime and durability is considered. For example, the obtained quality of the vapour at the turbine inlet can be lower than 1 which may cause a risk of condensation of liquid particles during the expansion resulting in erosion of the turbine blades. In the case of the volumetric expanders, the risk of expander damage resulting from the expansion of liquid phase is lower than in the case of turbines, however it is not advisable.

An promising way of improving the quality of a heat sources which feature floating characteristics may be the application of the heat storage systems (HSS). Dinçer and Rosen (2010) indicated that the main purpose of the heat storage system operation is a short or a long-term heat storage. The heat storage system can be charged by different heat sources (i.e., conventional, renewable and waste sources). The main component of the heat storage system is the heat storage device (HSD). Depending on the type of the heat storage device used, the heat may be stored for different periods of time, starting from a short-term (few hours) to a long-term periods (several months). According to Sharma (2009) technologies related to heat storage are up-to-date and thus they are intensively investigated in many scientific and development units. Such systems are used in the industry, however, according to the authors' knowledge, heat storage systems are not yet practically applied for powering ORC systems.

Heat storage devices can significantly differ in terms of the design, type of the applied heat storage substance and operating principle. As it was presented by Sarbu (2018) the basic features of heat storage devices are its capacity, power, efficiency, storage period, charge and discharge time and costs. The heat storage device should feature high power density (compact dimensions), simple design and high reliability. It should also be easy to transport and assembly and fully automated. By the physical phenomenon being the principle of heat storage device operation and the type of heat storage substance used, heat storage devices can be classified into the devices based on thermal phenomena (i.e. sensible and latent heat) and devices based on chemical phenomena (i.e. thermal chemical pipe line, heat of chemical reaction and chemical heat pumps). Different heat storage substances (i.e. liquids, solids, solid-liquid, liquid-gas, or solid-solid) are possible to be applied in devices based on thermal phenomena. The heat storage substance which is used in these heat storage devices should feature high values of thermal capacity and specific heat. It should also be chemically stable and resistant to cyclic changes in the thermal load resulting from the cyclic processes of charging and discharging. Sarbu (2018) indicated that some solids can be applied as heat storage substances e.g., rocks (granite or steatite), reinforced concrete, cast iron, cast steel as well as silica and magnesia fire bricks. Moreover, it is possible to apply liquids e.g., water, organic fluids and different types of oil (including hardening oils). Phase change materials (PCMs) such as organic, inorganic and eutectic substances (e.g., hydrated salts, paraffin, etc.) can also be applied, see Ushak and Fernández (2014). The heat storage device efficiency increases due to the beneficial effect of latent heat release during the phase transition if PCMs are applied as heat storage substances,.

The basic technical parameters (i.e. the operating temperature range, capacity, power, efficiency, storage period and cost) of the heat storage device depend on the device type and the type of heat storage substance used. Sarbu (2018) listed the typical parameters of the heat storage devices (see Table 1). The operating temperature of the heat storage devices varies in the range of 200—1200 °C (for solid heat storage substances), 20—260 °C (for liquids) and 20—120 °C (for PCMs). The design and operating principle of the heat storage devices which are applied in the industry is similar to the design of shell-and-tube heat exchangers. However, the difference is that the heat from the heat carrier is transferred to the heat storage substance instead of the second working fluid.

Table 1: Typical parameters of heat storage devices (adapted from Sarbu)

Type of device	Capacity	Power	Efficiency	Storage period	Cost
	kWh/t	MW	%		EUR/kW
Sensible (hot water)	10—50	0.001—10.0	50—90	Days/months	0.1—10
Phase-change material (PCM)	50—150	0.001—1.0	75—90	Hours/months	10—50
Chemical reactions	120—250	0.01—1.0	75—100	Hours/days	8—100

By temperature of the heat source carrier, ORC systems can be classified into systems powered by high- (more than 500 °C), medium- (250-500 °C), and low- (40-250 °C) temperature renewable or waste heat sources. The comparison of these temperatures with the operating temperatures of different types of heat storage devices shows that heat storage devices adopting solids and liquids as a heat storage substances are the most promising for combination with large industrial ORC systems. The application of the heat storage devices adopting PCMs to ORCs can be limited to small domestic devices due to the low range of operating temperature (up to ca. 120 °C).

The different applications of the heat storage devices in ORCs can be considered. They can be applied e.g., as a standby heat source or additional heat source used to improve the ORC system efficiency. Some designs were treated in more details by Kolasiński (2013). Selected issues related to the application of the long-term heat storage devices in domestic applications were also treated by Nemś (2018 and 2017). In the following part of the article, the results of experiment on powering the ORC system by heat storage device are presented.

2. EXPERIMENT ON POWERING ORC SYSTEM BY HEAT STORAGE DEVICE – DESCRIPTION AND RESULTS

The experimental investigations were carried out using a prototype of combined heat and power (CHP) ORC system adopting a multi-vane expander. This test-stand was comprehensively described by Kolasiński (2015). Figure 1 shows a simplified construction scheme of the test-stand. The main test-stand components are: a gas central heating boiler (featuring maximal thermal power of 24 kW) (1), a shell-and-tube evaporator (2), a working fluid pump (3), a reservoir of working fluid (4), a plate condenser (5), and a micro multi-vane expander connected to a DC generator (6). The working fluid is R123. The measurements are carried out using the following methods: temperatures are measured with the use of T-type thermocouples, pressures are measured with the use of tube pressure gauges. The flow rate of R123 as well as the flow rate of cooling and heating water are measured with the use of rotameters (see Figure 1 for the measurement sensor locations: p—manometer, t—thermocouple, V—rotameter).

The test stand is based on manual control of the operational parameters with the help of regulation valves. The heat source for this experimental system is hot water provided by the gas central heating boiler. The hot water circulates in the loop formed by the boiler and the shell of the shell-and-tube evaporator. The temperature of the heat source can be regulated in the range of 40–90 °C.

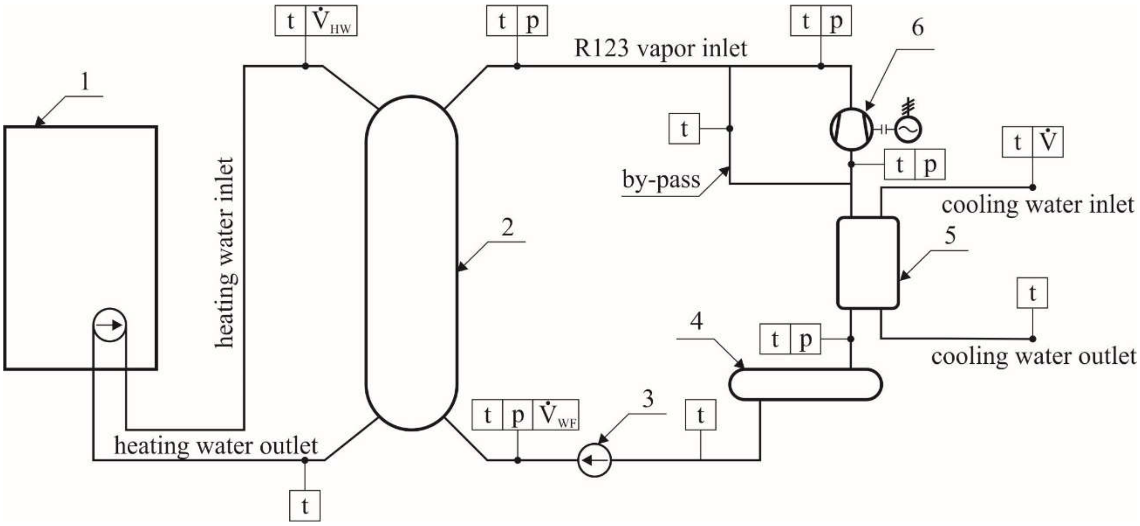

Figure 1: The simplified construction scheme of the test-stand. 1—gas central heating boiler; 2—shell-and-tube evaporator; 3—working fluid pump; 4—reservoir of working fluid; 5—plate condenser; 6—multi-vane expander with DC generator.

The working principle of the test-stand can be described on the basis of Figure 1. The hot water from the gas central heating boiler (1) is pumped to the shell of the evaporator (2). The liquid R123 is pumped (3) from the reservoir (4) to the evaporator coil (2), where it is heated by the hot water circulating in the evaporator shell. The pressurized vapour flows through pipes to the inlet of the multi-vane expander (6). After the expansion the vapour flows to the plate condenser (5). The condenser is cooled by cold water in an open cycle. Then the liquid flows to the reservoir (4) and the cycle is therefore complete. The expansion device is a micro four-vane air motor featuring a maximum power of 300 W. The expander was specially adapted for low-boiling working fluids, e.g., special seals and bearings were used. The expander is connected by a gas-tight clutch to a small DC generator. This expander requires a certain level of working fluid pressure at the inlet which is necessary to put the rotor in motion. As it was proved by Kolasiński (2016) in previous studies, the working fluid pressure at the inlet to the tested expander have to be higher than 1.5 bar. For lower values of pressure at the expanders' inlet, it was not possible to put the expanders' rotor in motion. Moreover, this expander features an optimum expansion ratio (i.e., the ratio of the pressure on the expanders' inlet to the pressure on the expanders' outlet) ranging from 3.5 up to 4.5.

The shell-and-tube evaporator (2) features the thermal power of 6 kW, the volume of the pipes of 6,6 dm^3 and the volume of the shell of 20,8 dm^3. In order to maximally limit the heat losses the evaporator is insulated with a layer of glass wool (5 cm thick). This evaporator can be treated as a heat storage device when the water contained inside the shell is hot and the valves at the inlet and the outlet of the evaporator are closed (i.e., there is no flow of working medium through the heat exchanger shell).

The main aim of this experiment was the analysis of the possibility of the application of the heat storage device for ORC system powering. The ORC system operation time was measured during the discharging of the heat storage device and the ORC system operation was observed during the experiment, i.e. the flow rate, pressure and temperature of R123 at the outlet of the exchanger and at the expanders' inlet and outlet were recorded. The experiments were carried out for the heat storage substance (water) temperature of 45 °C, 55 °C, 75 °C and 85 °C. After reaching the set value of water temperature, the boiler was switched off and the inlet and the outlet valve of the evaporator were closed. Then, the working fluid pump was started and the liquid working fluid was flowing through the coil of the evaporator. During all experiments, the flow of low-boiling working fluid was kept constant (150 l/h). The experiment consisted on measuring the expander operating time.

Figure 2a shows the variation of the working fluid pressure at the inlet of the expander during the experiment for different values of the water temperature (t_w), while Figure 2b shows these selected experimental results for which the working fluid pressure at the inlet of the expander was higher or equal to 1.5 bar (i.e., the minimum pressure needed for driving the expander).

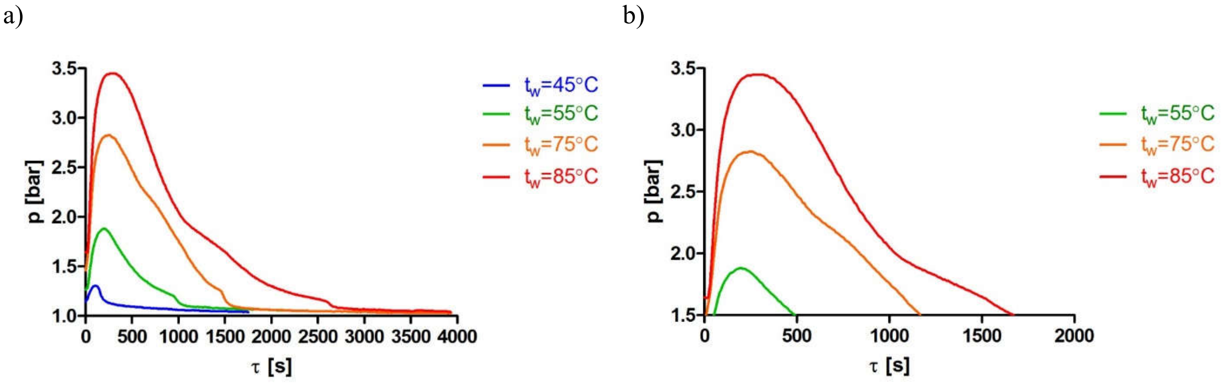

Figure 1: The variation of the working fluid pressure at the inlet of the expander during the experiment duration a) full experimental results, b) selected experimental results (limited to the pressure of 1.5 bar)

As can be seen in Figure 2a, the required working fluid pressure at the expander inlet was not obtained in all of the analysed cases (i.e., the minimum working fluid inlet pressure was not obtained in case of heat storage medium temperature of 45 °C – see, blue line in Figure 2a). Therefore, it was not possible to put the expander into operation during this experimental series.

In the following experimental series a higher pressure at the inlet to the expander was obtained, thus it was possible to put the expander into operation (see, Figure 2b). The experimental results proved that it is possible to power the ORC system adopting volumetric expander from the heat storage device. Depending on the thermal parameters of the heat storage medium, the working fluid pressure at the inlet to the expander and operating time of the ORC system varies in the following ranges:

- for the heat storage medium temperature of 55 °C (see, green line in Figure 2b) the maximum pressure at the inlet to the expander (1.9 bar) was obtained in 3rd minute of the experiment duration and the expander was operating for ca. 8 minutes,
- for the heat storage medium temperature of 75 °C (see, orange line in Figure 2b) the maximum pressure at the inlet to the expander (2.8 bar) was obtained in 4th minute of the experiment duration and the expander was operating for ca. 19 minutes,
- for the heat storage medium temperature of 85 °C (see, red line in Figure 2b) the maximum pressure at the inlet to the expander (3.4 bar) was obtained in 4th minute of the experiment duration and the expander was operating for ca. 27 minutes.

3. SUMMARY AND CONCLUSIONS

This paper presents the results of experimental analysis on possible application of the heat storage devices in ORC systems. Heat storage devices are especially promising for powering the ORC systems utilizing the heat sources featuring floating output and temperature characteristics, such as, e.g. waste or solar heat. The experiment on powering the ORC system by the heat storage device was conducted. During the experiments different temperatures of the heat storage medium were used. Depending on the temperature of the heat storage medium, different operating times of the ORC system and different thermodynamic parameters of low-boiling working fluid were obtained. The experimental results proved that it is possible to power the ORC system by the heat storage device only if the heat storage medium temperature is high enough to heat and evaporate the working fluid and obtain the minimum vapour pressure which is needed to drive the expander. It was found that the ORC system operating time ranged between 8 and 27 minutes depending on the heat storage medium temperature. The experiments were performed on a very small device in a limited range of experimental conditions. However, the experimental aim was achieved and the results are representative also for larger vapour power systems adopting volumetric expanders.

Encouraged by the obtained results, the author decided to continue the research on the application of heat storage devices in ORC systems.

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