Constant power production with an organic Rankine cycle from a fluctuating waste heat source by using thermal storage

K. Couvreur[1], J. Timmerman[1], W. Beyne[2], S. Gusev[1], M. De Paepe[2], W.D. Steinmann[3], and B. Vanslambrouck[1*]

[1]Department of Flow, Heat and Combustion Mechanics, Ghent University – UGent, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium

[2]Department of Flow, Heat and Combustion Mechanics, Ghent University – UGent, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

[3]Institute of Technical Thermodynamics, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

[*]Corresponding author: Bruno.Vanslambrouck@Ugent.be

Abstract

In energy intensive industries, organic Rankine cycle (ORC) systems can significantly increase energy efficiency and reduce carbon emissions by converting low- and medium-temperature waste heat to electricity. However, fluctuations in waste heat availability can negatively affect the operation of an ORC unit. By integrating intermediate thermal energy storage these fluctuations can be mitigated and part-load operation of the ORC unit can be avoided. This paper describes the design of a test rig to investigate combined LHS ORC systems and the set-up of future experiments. The test rig consists of a 110 kWh latent heat storage (LHS) system, connected to a 250 kW_e heater and a 11 kW_e ORC unit. For optimal integration and operation of LHS systems, effective operating strategies and methods to monitor the state of charge (SOC) need to be composed.

Keywords: waste heat recovery, organic Rankine cycle, thermal energy storage, latent heat storage.

Introduction

In 2013, 25% of the total energy consumption of the European Union could be allocated to the industry sector. In 2014, 20% of the greenhouse emissions originated from manufacturing processes [1]. A considerable amount of the industrial primary energy (20 – 50%) is lost in forms of low grade waste heat in large scale thermal systems [2]. However, by exchanging this waste heat between thermal processes or converting it to electricity, fossil fuel consumption and related emissions can be decreased. The recovered energy can be either reused directly in the same industrial site where it is produced, or it can be fed in a distribution network. Waste heat to power (WHP) systems such as ORC create opportunities to increase the energy efficiency in energy intensive industries and reduce emissions [3].

Typically, in WHP applications, two phase power cycles are frequently used to recuperate waste heat. Waste heat is recuperated and transferred to a working fluid of which the properties are adapted to the waste heat source temperature. Subsequently mechanical energy is generated in an expander coupled to an electric generator. Common and well developed power cycles include steam Rankine cycle, ORC and Kalina cycle. The ORC is considered as a viable technology for converting low- and medium-temperature heat to electricity for which it is difficult to apply the normal steam Rankine cycle [4, 5]. The working fluid is an organic fluid with a low boiling temperature, lower latent heat and a small specific volume compared to water, so the overall power generation system can be designed to be much smaller. Because of this advantage the ORC has been researched extensively since the 1960s.

The availability of the waste heat can significantly fluctuate (Figure 1). While fluctuations are inherent to industrial processes, they negatively affect the operation of ORC systems [6]. However, WHP systems and ORC systems in particular are commonly designed for a single operating point (nominal load) disregarding the waste heat fluctuations. Moreover, system components and working fluids are mostly optimized to increase the cycle efficiency at a certain nominal load [7]. This nominal load is either defined by the upper boundary or by the average values of the operation range. As a result, WHP systems subjected to thermal power fluctuations often operate at part load conditions (off-design) with reduced efficiency [8]. When large thermal power fluctuations occur, a complete bypass of the WHR system might be necessary. Overall, this leads to lower heat recovery which negatively affects the economic feasibility for the implementation of WHP systems. A steady heat load close to the nominal load is thus preferable to operate an ORC.

To keep the WHP system running at constant load under fluctuating waste heat availability, either the mass flows through the system can be manipulated, or thermal storage can be integrated [6, 9]. By integration of a thermal energy storage (TES) system, the fluctuations in heat availability for the WHP system can be flattened. In periods with high waste heat availability, the heat in excess of the nominal load of the WHP is stored in the TES, while in periods with low waste heat availability, the TES complements the heat deficit. As a result, the size of the WHP can be reduced, the duration and depth of part-load operation can be decreased.[9]. Moreover, the mismatch between waste heat availability and electricity demand can be bridged. Also the supply of heat to the WHP system can be extended [10].

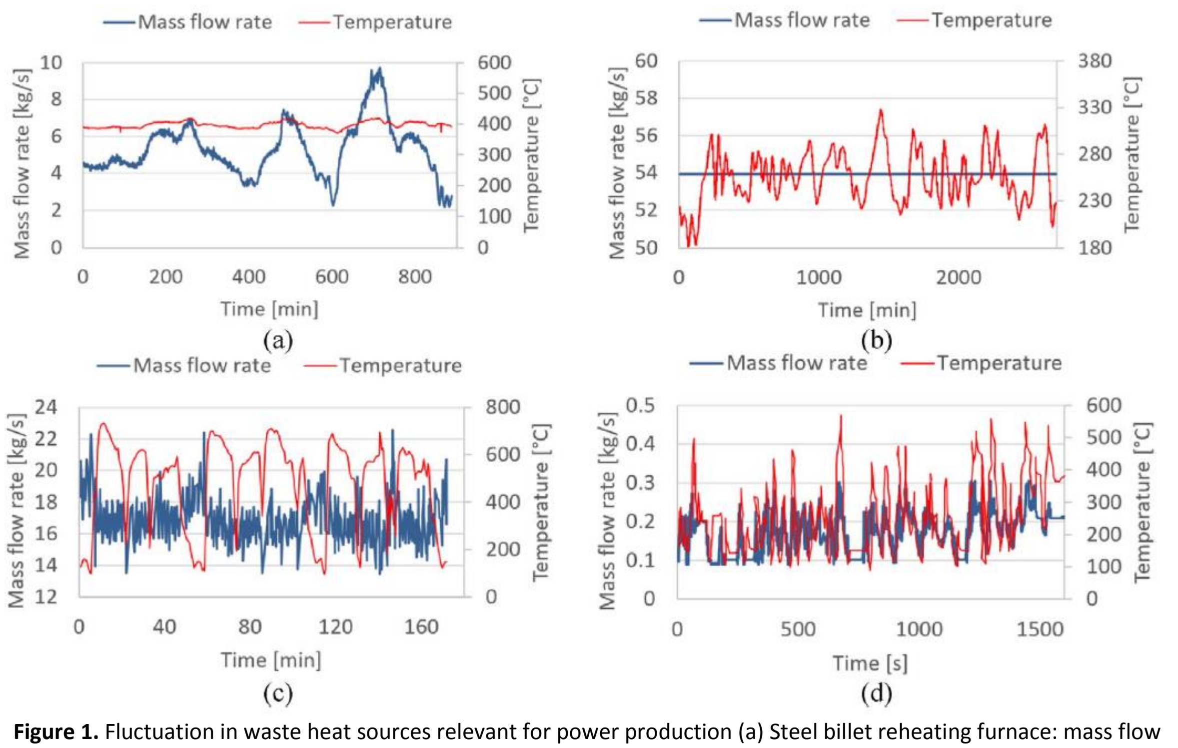

Figure 1. Fluctuation in waste heat sources relevant for power production (a) Steel billet reheating furnace: mass flow fluctuations, (b) Clinker cooling: temperature fluctuations, (c) EAF (after water cooling system): fluctuations of both mass flow and temperature, (d) IC engine exhaust: fast fluctuations. Derived from [6].

TES systems can be classified as sensible, latent or thermochemical [11]. Thermochemical storage systems are still in the research phase, but it can potentially store more energy than sensible or LHS systems due to the heat of reaction [12]. In sensible heat systems (water buffers, concrete blocks, molten salts, etc.) heat is stored by raising the temperature of a storage medium. Consequently, the amount of heat that can be stored depends on the specific heat capacity of the storage medium and is a strong function of the available temperature difference. Latent heat storage (LHS), using phase change materials (PCMs), allows to store more heat than sensible storage due to its higher energy density. Moreover, during charging or discharging the mean temperature of a latent heat storage system stays on a nearly constant level, as long as part of the storage medium is still in the transition phase, which is not the case for sensible heat storage. As a consequence, LHS can act as a heat sink (to cool down a waste heat stream) or heat source (to evaporate the ORC fluid) at nearly constant temperature.

Various studies on TES systems for smoothing fluctuations of waste heat have been conducted. Integration of PCM technology has been investigated by *Nardin et al.* and *Dal Magro et al.* [7, 13, 14]. In [13] PCMs are used to reduce the variability of off-gas temperatures and thermal powers from the electric arc furnace (EAF) process, while in [14] they inserted in the off-gas line of a continuous charge EAF process a temperature smoothing device based on PCMs. The integration of this device enhances the downstream energy recovery system where the reduced fluctuations increased the steam turbine load factor. *Dal Magro et al.* also investigated the impact of retrofitting a PCM based technology in a billet reheating furnace on the existing ORC. Results showed that the introduction of the PCM based technology allows the capacity factor to increase from 38% to 52% with an average thermal efficiency increase from 15.5% to 16.4% [7]. Other TES systems are investigated in *Sung et al.* and *Ramirez et al.*[10, 15]. In [15] a 200 kW ORC is installed in a steel processing plant to recover the energy from flue gases. A water thermal storage tank with 1-ton capacity was installed after a flue gas heat exchanger to suppress variation of the heat source and prevent abrupt temperature increases at the inlet of the ORC evaporator. Results show that the fluctuations are successfully suppressed by the thermal storage. In [10] a 1.8MW ORC is installed along with a waste heat recovery unit in a steel mill to recover waste heat from the fumes of an EAF. A steam accumulator of 150m³ was implemented between the heat recovery unit and the ORC to reduce fast transients in the waste heat and extend the supply over longer periods. From the accumulator steam is sent to the ORC unit and its flow is controlled to maintain pressure and flow as constant as possible. The relatively steady discharge allows the ORC to provide a power output with only minor oscillations. *Pili et al.* [9] performed a techno-economic analysis of waste heat recovery with ORC from fluctuating industrial sources, with and without thermal storage. Different configurations for three applications are compared in terms of levelized cost of electricity and CO_2-savings. There is no best solution which serves all applications, but thermal storage seems to be economically and environmentally beneficial when the heat source is affected by large fluctuations in temperature.

Results and discussion

A fast method to check the economic benefits of a storage system applied for the reduction of the primary energy demand is by means of the payback time which can be estimated by:

$$t_{payback} = \frac{1}{n_{daily} \cdot n_{days}} \cdot \frac{c_{storage}}{c_{thermal}} \qquad (1)$$

With $t_{payback}$ the payback time [years], $c_{storage}$ the capacity specific costs of the storage system [€/kWh], $c_{thermal}$ the specific costs for thermal energy [€/kWh], n_{daily} the number of cycles per day and n_{days} the number of days per year with n_{daily} cycles.

An example calculation for a LHS based on the parameters in Table 1 results in a payback time of 10.4 years, which is insufficient compared to the currently demanded payback times in industry of 3-5 years. The major cost component is the expensive equipment rather than the storage material. According to literature [16] the costs for LHS systems are ranging between 10 – 50 €/kWh but in practice costs for industrial scale systems can be higher. This leads to LHS systems only being economically viable for applications with a high number of cycles. In order for LHS to enter the market as a viable solution the costs of the equipment should be lowered.

Table 1. Parameters and values used in Equation 1.

Parameter – Meaning – [unit]	**Value**
$c_{storage}$ - the capacity specific costs of the storage system [€/kWh]	100
$c_{thermal}$ - the specific costs for thermal energy [€/kWh]	0.02
n_{daily} - the number of cycles per day [-]	2
n_{days} - the number of days per year with n_{daily} cycles [-]	260

LHS could be a viable solution in situations where the size of WHP system components can be reduced with the integration of LHS. The required nominal load of the WHP system decreases and at this reduced nominal load, the LHS causes the depth and duration of part-load operation to decrease, which results in a more efficient conversion to electricity. The decrease of capital cost is expected to have a greater effect on the economic feasibility than the increase in revenues from electricity production [9]. This saved investment cost can then be used for a LHS.

As an example, the conversion of waste heat from a cement plant is considered. At the Heidelberger Zement AG Plant a 1.5 MW ORC recovers the heat available from the grate cooler and generates heat on a continuous basis without interfering with the clinker production process. Heat is transferred to the ORC by means of a thermal oil flow circulating in a closed loop system (Figure 2).

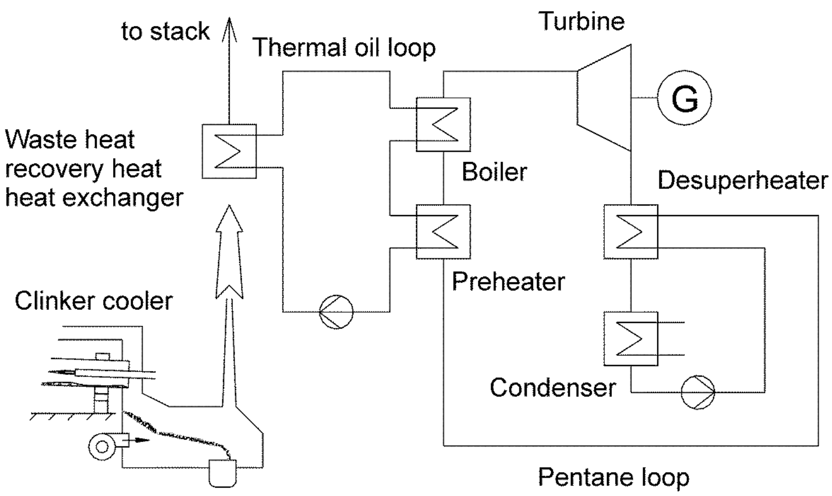

Figure 2. Clinker cooler heat recovery system at the Heidelberger Zement factory in Lengfurt. Adapted from [17].

However, this waste heat is continuously varying between temperatures ranging from 180°C to 340°C, causing the thermal oil to fluctuate between 120°C to 230°C (Figure 3). Coping with such fluctuations, the ORC generates between 400 kW and 1500 kW [17]. Instead of installing a 1.5 MW ORC and dealing with part load operation a smaller unit could be installed and thermal power fluctuations can be reduced with the integration of a PCM storage. As such it could be possible to install a 980 kW ORC at an estimated cost of 3M € while a 1.5 MW ORC is 0.6-1M € more expensive. With the combination of a PCM storage and a smaller ORC the efficiency is improved by avoiding part load operation. With the cost savings by reducing the size of the ORC it is possible to integrate a 1500kWh PCM storage at 100€/kWh which is needed to keep the temperature of the waste gases after the PCM storage constant.

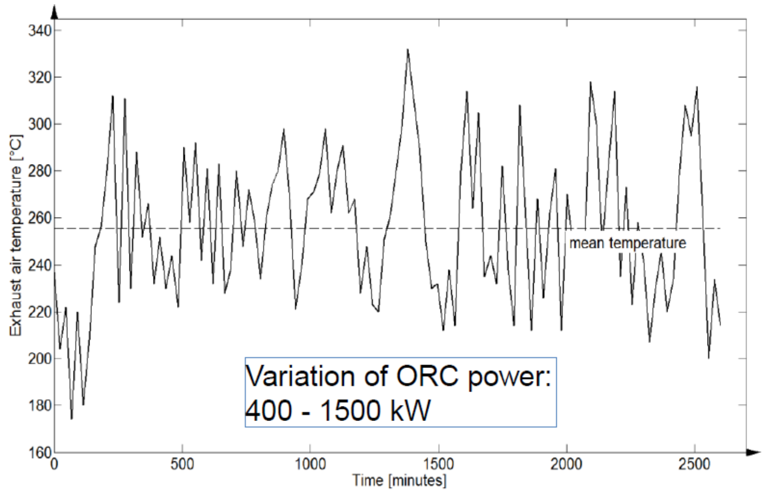

Figure 3. Temperature variations of the exhaust gases at the Heidelberger Zement factory in Lengfurt. Due to this variations ORC power varies between 400-1500kW. Adapted from [17].

Test rig – Simulation and control

To evaluate the behaviour and performance of a combined LHS ORC system a pilot scale system is installed at Ghent University Campus Kortrijk within the frame of the European CORNET ShortStore project. The system consists of: a 110 kWh LHS (Figure 6), a 250 kW electric heater which can simulate a fluctuating waste heat source and a 11 kW_e ORC, interconnected via a thermal oil circuit (Figure 5). The characteristics of the LHS and ORC are listed in Table 2. A performant control strategy will be developed enabling stable ORC operation under fluctuating waste heat conditions. For optimal operation of these systems effective operating strategies and methods to monitor the state of charge (SOC) are required. However, SOC estimation for LHTS systems during operation is the bottleneck for its application in industry [18]. A heat exchanger with the environment will act as a heat sink to extract heat during LHS discharging and the electric heater as a heat source for charging the LHS. The SOC will be estimated based on continuous monitoring of PCM temperatures orthogonally placed at different axial positions in the LHS based on the method described in *Barz et al.* [18].

Mathematical simulations of the finned shell and tube LHS are performed with a dynamic 2D model in Python based on the apparent heat capacity method. For all tubes of the LHS unit, equal flow of the HTF and equal temperature distribution on both the shell and tube side is assumed. Thus, in the model only one tube is considered and boundary effects near to the limit of the storage device, for example, energy losses to the surrounding, are ignored. The fins are considered only indirectly by an increased heat conduction in the PCM. As a first step, the (dis)charging behaviour of the LHS is analysed at variable mass flow rates and inlet oil temperatures. The results for discharging the LHS are presented in Figure 4. The initial PCM temperature is set at 230°C and is in a completely molten state. Full lines represent the outlet oil temperature and the dotted lines the extracted thermal power. On the upper graph the inlet oil temperature is kept constant while the oil mass flow varies from 1.5 kg/s to 3 kg/s. With increasing mass flow rate the initial extracted thermal power increases but rapidly decreases over time. The outlet oil temperature decreases with increasing mass flow rate. The sharp decrease of both extracted thermal power and outlet oil temperature after 2000s with a mass flow rate of 3 kg/s is due to the complete PCM solidification and only sensible heat is available after 2000s. On the lower graph the mass flow is constant while the inlet oil temperature varies from 100°C to 210°C. With increasing temperature difference between inlet oil temperature and PCM temperatures the less constant the outlet oil temperature is. Moreover, initial extracted powers increase but rapidly decreases due to faster PCM solidification rates.

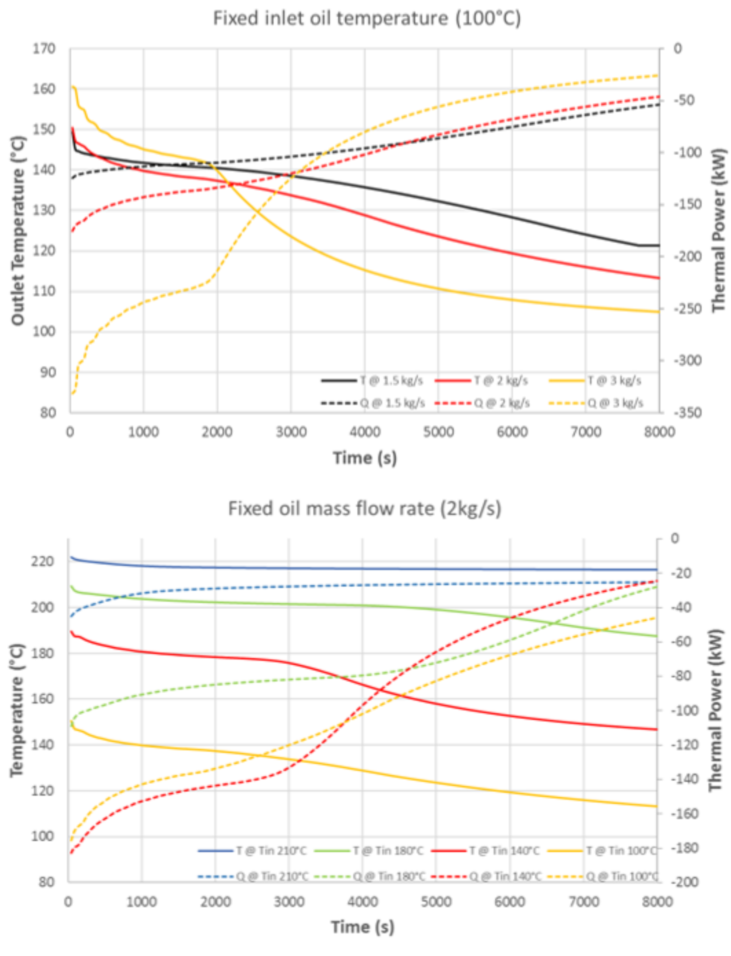

Figure 4. Simulation results of the LHS system. The PCM is in an initial completely molten state at 230°C. Upper: Outlet oil temperature and extracted power are plotted for different mass flow rates at constant inlet oil temperature. Lower: Outlet oil temperature and extracted power are plotted for different inlet oil temperatures at constant mass flow rate.

Note, that the oil flow direction in the LHS is different for charging and discharging due to the inherent characteristics of the PCM. During charging the PCM melts and its volume increases. To prevent damage to the storage equipment due to changing PCM volumes, during charging the HTF inlet is at the top of the LHS, while during discharging the HTF inlet is at the bottom.

In a second step the capability of the LHS in reducing fluctuations in waste heat availability due to variations in mass flow rate or temperature are investigated. In a third step, the main aim of this research, a control procedure will be developed to enable stable ORC operation under fluctuating waste heat conditions by charging the LHS when there is an excess of waste heat and discharging the LHS when there is not enough waste heat.

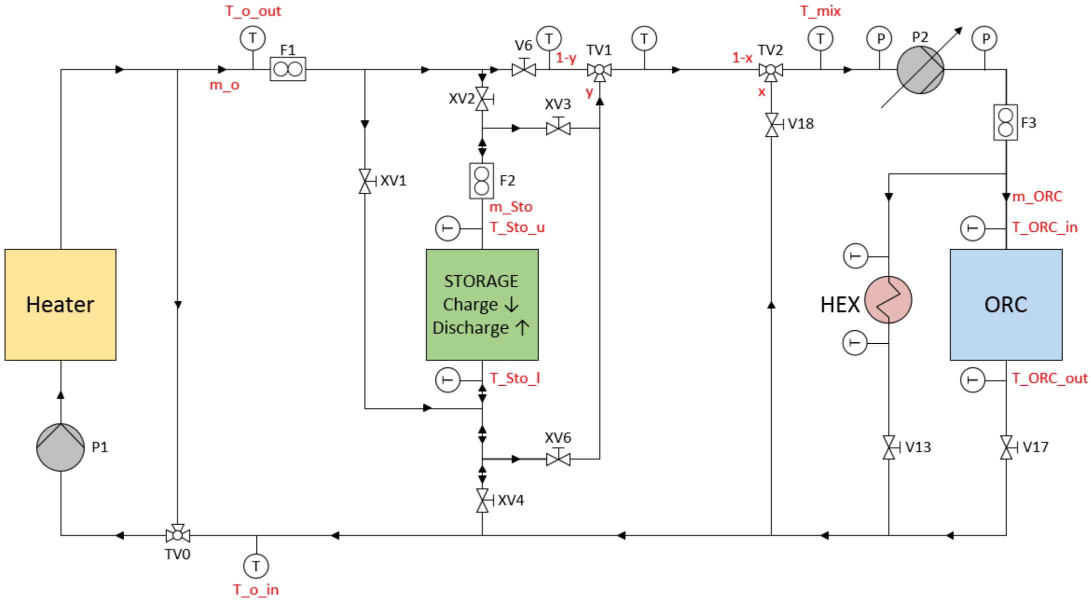

Figure 5. Schematic of the test set-up. Flow directions in the system are indicated by arrows. (Motorised) Globe valves are indicated with '(X)V', three way valves with 'TV', flowmeters with 'F' and temperature measurements with 'T'.

Figure 6. Picture of the LHS installed at UGhent Campus Kortrijk.

A schematic overview the test set-up is presented in Figure 5. The target operating conditions of the ORC are an incoming oil temperature (*T_ORC_in*) of 130-140°C at a mass flow rate of 2 to 3 kg/s. Because the LHS will be used near the PCM melting temperature (223°C) and *T_ORC_in* is limited to 140°C to prevent damage to the evaporator and expander a basic control mechanism is implemented. The return of the ORC (*T_ORC_out*) is partly mixed at valve '*TV2*' with the oil coming from the heater and storage to reach a mixing temperature (*T_mix*) equal to the target operating temperature. Changing the amount of mixing will result in changing mass flow rates in the LHS and/or heater and accordingly oil temperatures after the heater and LHS will change. Depending on the temperature changes the control system is needed to adjust the position of the three way valves in order to control *T_mix* as close as possible to the target operation temperature.

Table 2. ORC and LHS characteristics.

ORC characteristics		LHS characteristics	
Working fluid	R245fa	**PCM material**	Eutectic mixture $KNO_3/NaNO_3$
Maximum evaporator pressure	14 bar	**PCM melting temperature**	223°C
Max generator power	11 kW_e	**PCM volume**	2 m^3
		LHS thermal capacity	112 kWh (latent heat) 220 kWh in temperature range 180-250°C

Summary/Conclusions

ORC systems are commonly designed for a single nominal load disregarding the waste heat fluctuations. LHS systems are able to decrease this nominal load and increase the conversion efficiency. The described pilot scale set-up is installed at UGent Campus Kortrijk and serves as a demonstration for the characterization, integration and operation of a combined LHS-ORC system. Heat is generated by an electrical heater and is controlled to simulate a fluctuating waste heat profile. A control strategy will be developed to operate the ORC at constant heat load. The test set-up will be used to characterize the behaviour of a large scale LHS system with SOC estimations based on the method described in [18]. Therefore, this research contributes to the further development of waste heat recovery technologies.

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