Commissioning and Preliminary Experimental Investigation of an Organic Rankine Cycle Set-up with Oil-flooded Expansion

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Abstract:
The expander is a critical component of an organic Rankine cycle system as its performance in converting work from a high-pressure vapour greatly affects the overall efficiency of the system. Therefore, improving expander performance is one of the key elements in optimizing organic Rankine cycle systems. The use of oil-flooded expansion, i.e. adding significant amounts (by mass fraction) of lubricant oil to the working fluid before it enters the expander, is one of the concepts to achieve increased expander efficiency. In this work, an experimental organic Rankine cycle set-up has been built with an independent lubricant oil loop that allows testing the influence of oil flooding on a single-screw expander. The heat source is simulated by an electric heater with a maximum capacity of 250 kWe and uses a thermal oil as the heat transfer fluid. The working fluid under consideration is the low-GWP refrigerant R1233zd(E) as a potential replacement for R245fa. Pressures, temperatures, mass flow rates and power measurements are logged. The data reduction and method used for altering the set-points is discussed. In addition, a preliminary experimental campaign has been conducted to investigate the possible influence of different oil flooding ratios at different pressure levels. The initial results show a decreasing trend in net specific power, cycle efficiency and isentropic efficiency for increasing flooding, and no observable effects on isothermal expansion are found. Additional research is required to eliminate the influence of certain testing conditions and to provide a more in-depth conclusion on the impact of liquid flooding on organic Rankine cycle performance.

Keywords:
Experimental, Isothermal expansion, Oil flooding, Organic Rankine cycle, R1233zd(E).

1. Introduction

It is well documented that human activities negatively impact the environment [1]. Yet, addressing energy demand while ensuring sustainability is an open challenge. Different agreements and targets were established in order to meet this challenge. The 2030 climate and energy framework set out by the EU is one example [2] of agreement that focuses on three main targets: reducing greenhouse gas emissions, reaching a high gross final energy use percentage of renewables and improving energy efficiency.

One way to have an impact on all the aforementioned targets is by altering aspects of electricity generation. Instead of using fossil fuels for heat generation, waste heat or heat from renewables such as solar and geothermal can be employed as more sustainable heat sources. However, in order to effectively exploit these low-grade heat sources, which consist of low-to-medium temperature heat

(80-200°C) [3], more suitable heat conversion technologies need to be considered. The Rankine cycle used in conventional thermal power plants is only efficient at high temperatures [4]. A possible answer is found in the organic Rankine cycle (ORC).

The ORC is considered a mature technology, but the adoption rate in practical applications still has the potential for further growth through improving the efficiency of the system and exploring advanced cycle configurations. Liquid flooded expansion (LFE) is one of these concepts to increase system efficiency. In conventional ORCs, oil injection can be present in the expander for lubrication purposes, and the injected amount of oil accounts for only 1-5% of the total mass flow through the system. However, in an ORC system with LFE, the flooding medium (i.e. lubricant oil) is not injected into the expander, but mixed with the working fluid vapour before entering the expander. Furthermore, a large amount of oil is used, which will alter the expansion process [5].

The addition of oil has two theoretical benefits. Firstly, the oil acts as a thermal buffer pushing the expansion process towards a quasi-isothermal expansion yielding higher expander outlet temperatures (favouring the use of internal regeneration) and increased expander power output (compared to an adiabatic process). Secondly, friction and leakage losses which are detrimental to the expander's performance are reduced due to more favourable oil distribution inside the expander.

In this work, a theoretical background to LFE and its possible benefits is first provided in Section 2. As previous experimental studies on LFE, especially on screw-type expanders and ORC performance, are limited, an experimental set-up was built to fill this gap in literature. In Section 3, the set-up as well as the experimental campaign are discussed. The focus of this work lies on commissioning this ORC set-up and developing a method for altering set-points. In Section 4, a preliminary set of experimental results of LFE on a modified single-screw expander is shared.

2. Expansion process

2.1. Single-screw expander

The main goal of a heat-to-power application is maximizing the net power output [6]. Therefore, the expander is a key component of an ORC system as this component enables the extraction of work from the working fluid. Improving expander performance is therefore key in further optimization of ORC systems. For smaller scale units (i.e. less than 50kW [7]), volumetric expanders are proven to be more cost effective than turbo-expanders [3, 8]. Ziviani et al. [3] investigated differences between possible volumetric expanders and stated that performance is affected by internal losses (such as leakages, friction and heat loss) and the operating condition (i.e. applied pressure ratio over the expander). They also concluded that a single-screw expander (SSE) has important advantages over other expanders such as high volumetric efficiency and low leakages.

2.2. Isothermal expansion

In addition to the expander, the expansion process itself can be altered as well. Two limiting cases for the expansion process are the adiabatic and the isothermal expansion, as illustrated in a pressure-specific volume diagram, depicted in Fig. 1. As can be seen in the figure, the area under the curve of the isothermal process (where temperature is kept constant) is larger than that for the adiabatic process (a process without heat transfer), meaning that more work can be extracted from the fluid using the former process. Moreover, an adiabatic process cannot be reached in practice as there is always a non-negligible heat transfer between working fluid and expander [9]. Another advantage of an isothermal expansion over an adiabatic expansion is that it will result in a higher expander outlet temperature. This favours the use of internal regeneration, which improves thermal efficiency.

To achieve isothermal expansion, heat needs to be transferred to the working fluid while it expands [10]. This can be realized by heating the expander surface or by adding a second medium with a higher heat capacity to the working fluid vapour. In the latter, the added fluid will act as a thermal buffer, meaning that it will recover the temperature drop due to expansion of the working fluid. However,

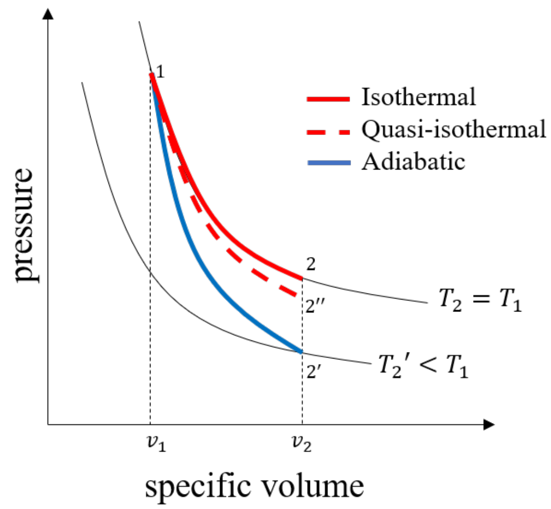

Figure 1: Comparison of isothermal and adiabatic expansion on a pressure-specific volume diagram.

due to practical limitations such as finite surface area of the expander or finite heat capacity of the flooding medium, only a quasi-isothermal expansion process can be reached in reality (see Fig. 1).

2.3. Liquid flooded expansion

2.3.1. Practical implementation

As friction losses and internal leakages are detrimental to expander performance, proper lubrication is vital [11]. This is where liquid flooded expansion (LFE) can have a positive influence on ORC efficiency and performance. In an ORC system with LFE (ORCLFE), a significant amount of oil is mixed with the working fluid vapour before entering the expander. The oil acts as a lubricant, thus reducing friction and leakage losses. In addition, the oil also acts as a thermal buffer thus pushing the expansion process towards a quasi-isothermal one, favouring the use of internal regeneration and increasing the expander power output.

In a conventional ORC, oil is injected into the expander by the use of an oil pump (and again extracted after the expander) or permanently mixed with the working fluid [12]. In the case of an ORCLFE, the oil is added to the working fluid before entering the expander and again separated from it after expansion. A separate oil circulation loop is present, which includes a pump for oil circulation and an oil heater to heat up the oil to the same temperature as the working fluid.

2.3.2. Previous efforts related to organic Rankine cycle systems

Feng et al. [13] stated that few works attempted to take into account the effect of lubricant oil on ORC operation. As lubricant oil can blend with working fluids, it can also affect the system behaviour. According to their results, an increase in scroll expander isentropic efficiency but a decrease in expander shaft power and electrical power occurs for increasing lubricant oil ratio.

Yang et al. [14] investigated the impact of different lubricant oil-concentrations on system performance and on individual components behaviour. Measurements were done with two degrees of freedom: mass flow rate and expander rotational speed. Lubricant oil was injected into the system from the scroll expander side, of which a part circulated with the refrigerant, as they did not add an additional oil pump or separator. They found that for an increase in lubricant oil ratio, expander isentropic efficiency improved constantly. A peak of cycle thermal efficiency was reached for the maximum tested lubricant oil charge.

Woodland et al. [15] developed a thermodynamic model to compare ORCLFE with conventional ORC technology for a range of working fluids. Their results indicated that an ORCLFE always leads to improved cycle efficiency for an optimal amount of flooding. The problem with low expander exhaust quality of wet working fluids is also eliminated due to the more isothermal expansion.

Ziviani et al. [9, 16] developed models to investigate LFE on SSEs. In a first work, a thermodynamic cycle model was developed to check the potential theoretical improvements on thermodynamic performance and work output of an ORCLFE compared to a baseline ORC with internal regeneration. The refrigerants investigated were R245fa and R1233zd(E). The cycle model was employed over a range of flooding ratios (y_o) and built-in expander volume ratios (BIVR):

$$y_o = \frac{\dot{m}_o}{\dot{m}_r} \tag{1}$$

$$BIVR = \frac{V_{EC;end}}{V_{EC;start}} \tag{2}$$

with $\dot{m}_o$ lubricant oil mass flow rate and $\dot{m}_r$ the refrigerant mass flow rate. In (2) the BIVR is defined as the ratio of the expander chamber volume at the end of expansion (VEC;end) to the expander chamber volume at the start of expansion (VEC;start). Overall, it was found that there was a significant impact on cycle efficiency. Cycle efficiency improved with 6.71% for R245fa and 2.90% for R1233zd(E). In a second work a semi-empirical model for the expander was incorporated to account for the presence of oil, friction and heat losses and internal volume ratio. The refrigerants tested were R1234ze(Z), R1233zd(E) and R1336mzz(Z). It was found that the optimal internal volume ratio lies between 4 and 6 for liquid flooded conditions. The findings concerning cycle efficiency were similar to the ones from their previous study. In addition, oil flooding of the expander resulted in proper lubrication, reducing mechanical losses in the expander, and led to increased net power output.
Experimental research on ORCLFE employing a screw-type expander is lacking. Therefore, based on the work of Ziviani et al. [9], a subcritical ORC set-up with LFE was built to be able to perform experimental investigations. Real set-up performance will differ from the theoretical one due to assumptions that were made in the model. Some examples: pressure drops over the heat exchangers and line sets were neglected, the lubricant oil was considered to be incompressible and the ideal gas model was used for the refrigerant.

3. Experimental investigation

3.1. Test facility

The ORCLFE set-up, built using off-the-shelf components, consists out of four loops: a working fluid, heating, cooling and oil circulation loop. A hydraulic scheme of the set-up is given in Fig. 2. The working fluid loop is the part of the ORC unit which contains the refrigerant and the basic ORC components (pump, evaporator, expander and condenser). The working fluid under consideration is R1233zd(E), a low-GWP working fluid as potential replacement for R245fa. As the influence of oil addition is tested, an oil circulation loop with separate pump, oil cooler and heater is also present. The oil used is SAE 20W50 and is mixed with the refrigerant before entering the expander. Plate heat exchangers are used as condenser, evaporator, recuperator and oil heater. A static mixer is employed to ensure a homogeneous mixture of refrigerant vapour and lubricant oil. Separation of the two fluids is done by a gravitational oil separator. A subcooler (which is also a plate heat exchanger) is present at the suction side of the pump to ensure sufficient subcooling such that there are no cavitation issues at the pump. The heat source of the evaporator and oil heater is simulated by an electric heater, having a maximum heating capacity of 250kWe. Therminol 66 is used as heating oil, with a maximum flow rate of 14m^3/h at the maximum temperature of 340°C. Inlet heat source temperature and mass flow rate can be controlled. For the cooling, a roof-top air cooled condenser is used, with a rated capacity of 480kW at 20°C ambient. The cooling liquid through the condenser is a water and ethylene-glycol mixture. Cooling mass flow rate can be controlled. As the inlet temperature of the cooling liquid is directly related to the outdoor conditions, this parameter cannot be controlled. The chiller, used to cool the subcooler, also uses a water-ethylene-glycol mixture to cool down the refrigerant.

The SSE that is employed is the one elaborated in the work of Ziviani et al. [11], which was already experimentally and numerically characterized. A standard single-screw air compressor was converted in order to operate as an expander. Some further alterations were done to improve its performance such as enlargement of the expander discharge port. The SSE has an BIVR of 5.3. Some practical limits apply to the pressure ratio that can be applied over the expander. For safety reasons, the upper limit is 1200kPa at the expander suction side and 300kPa at the discharge side. An 11kWe generator is coupled to the expander.

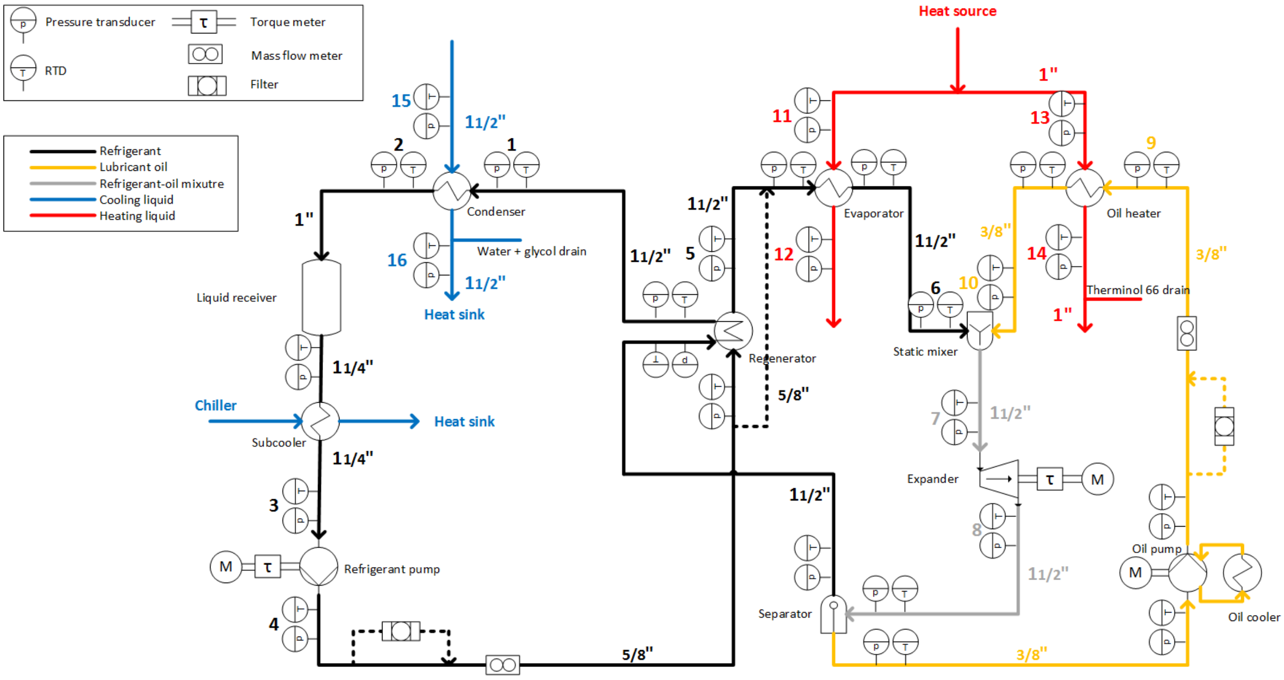

Figure 2: Hydraulic scheme of test set-up.

3.2. Experimental campaign

3.2.1. Steady-state and uncertainty analysis

When the ORC set-up is started, it takes some time before steady-state operation is reached. Steady-state operation means that the different properties (such as pressure and temperature) do not vary in time anymore. However, as data is taken from an experimental set-up, this condition will never be reached and a more practical approach to deduce steady-state is required (described in detail by Lecompte et al. [17]). The standard deviations of specified properties (12 in total) within a representative steady-state zone are calculated and will serve as reference. For every measured sample of these 12 properties, a forward-moving standard deviation is calculated. The latter is then compared to its reference for identifying the actual steady-state zones. Finally, the steady-state points are calculated as the average of the samples in the steady-state zones.

Sensors are used to measure the different properties of the set-up. These have an uncertainty interval around the measured value (X_m):

$$X = X_m \pm \delta X \tag{3}$$

with δX the uncertainty on the measurement. As the variables of interest are calculated from the measured ones, these will therefore also have a certain absolute uncertainty (U), calculated according to [18]:

$$U_K = \sqrt{\sum_{i=1}^{N} (\frac{\partial K}{\partial X_i} \cdot U_{X_i})^2} \tag{4}$$

where the variable K is a function of the variables X_i; i=1..N.

3.2.2. Data reduction

Temperature, pressure and mass flow sensors are implemented on the set-up. Their positions are indicated on Fig. 2 and their type and uncertainties (on the measurement value) are represented in Table 1. Pump and generator powers are read from variable frequency drives. From these measured variables, efficiencies and other performance parameters of the ORCLFE can be derived. These are evaluated in function of the amount of oil added to the refrigerant (represented by y_o) and the pressure ratio over the expander, which is defined as the pressure at the suction side of the expander ($p_{bef,exp}$) divided by the pressure at the discharge side ($p_{aft,exp}$):

$$PR = \frac{p_{bef,exp}}{p_{aft,exp}} \tag{5}$$

Table 1: Sensor uncertainties.

Measured variable	Sensor type	Uncertainty
$\dot{m}_r$, $\dot{m}_o$	Coriolis mass flow meter	±0.09%
$\dot{m}_{hf}$	Pressure orifice	±1%
T	Resistance temperature detector	±0.2°C
p	Absolute pressure sensor	±1.6kPa

The performance parameters are presented in Table 2. Here, $\dot{W}_{net}$ is the difference between the power generated by the expander and the sum of the powers used by the refrigerant and oil pump. $\dot{Q}_{in}$ is the sum of the heat added to the refrigerant and to the lubricant oil by the heat source. The Carnot efficiency used to determine the Second Law efficiency is the theoretical maximum efficiency that can be reached with the cold and hot source present (when assuming infinite heat capacities of cold and hot source), characterized by respectively the temperature of the cooling fluid (cf) at the condenser (cd) inlet and the temperature of the heating fluid (hf) at the evaporator (ev) inlet ($\eta_{Carnot} = 1 - T_{bef,cd,cf}/T_{bef,ev,hf}$). Isothermal efficiency of the expander is equal to the ratio of the power generated by the actual expansion process to the power generated by an isothermal process. Similarly, the isentropic expander efficiency is defined by the ratio of the actual power to the power generated by an isentropic process:

Table 2: Performance parameters.

Performance parameter	Formula
Temperature ratio	$TR = \frac{T_{aft,exp}}{T_{bef,exp}}$
ORC cycle efficiency	$\eta_{ORCLFE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
Second Law efficiency	$\eta_{II,ORCLFE} = \frac{\eta_{ORCLFE}}{\eta_{Carnot}}$
Expander isothermal efficiency	$\eta_{exp,isoth} = \frac{\dot{W}_{exp}}{\dot{W}_{exp,isoth}}$
Expander isentropic efficiency	$\eta_{exp,is} = \frac{\dot{W}_{exp}}{\dot{W}_{exp,is}}$

3.3. Altering set-points

The influence of oil flooding on expander performance at different pressure ratios over the expander is investigated. However, these parameters cannot be controlled independently and thus need to be obtained by altering other parameters of the set-up.
The pressure ratio across the expander is a direct function of the pressure before and after the expander. The pressure ratio can thus be altered using two different methods, *i.e.* changing the inlet

pressure of the expander or changing its outlet pressure. As changing the condenser conditions did not have much influence on expander outlet pressure, the pressure ratio is varied by varying the expander inlet pressure (through alteration of refrigerant pump and expander speed, and the heat source conditions).
The flooding ratio is directly determined by the mass flow rate of oil and mass flow rate of refrigerant. The latter is set by the refrigerant pump and expander rotational speed. As both these variables are held fixed at a certain pressure ratio, the flooding ratio is altered by altering the mass flow rate of oil, which is done by changing oil pump rotational speed. It should be noted that at an oil pumping speed above 250rpm, resonance occurred in the oil piping. Therefore, oil pumping speed and as a result flooding ratios that could be tested, were limited.

4. Preliminary results and discussion

Net specific power generated by the cycle decreases with increasing flooding ratio (Fig. 3). The decrease in net power is due to the combined effect of a decrease in generated expander power and an increase in oil pumping power up to a certain level (Fig. 4). Refrigerant pumping power has limited effect. A possible explanation for the decrease in expander power is as follows. It was difficult to keep the expander inlet pressure constant when flooding was increased on the current set-up. For increased flooding, the expander inlet pressure dropped which corresponds to a drop in power (area under pv-diagram in Fig. 1 reduces). It is possible that a potential increase in power due to oil flooding is nullified by the decrease in power due to the decrease in pressure [19]. However, further investigation is required.

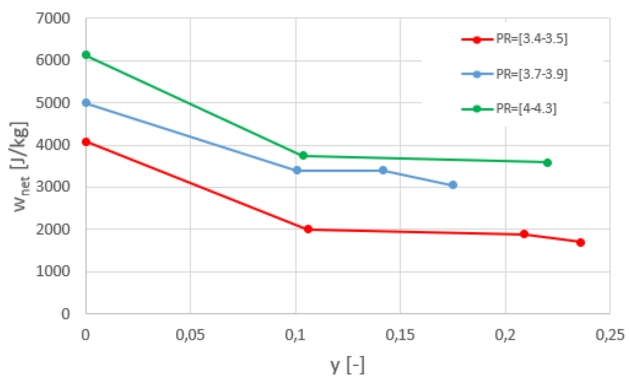

Figure 3: Net specific power in function of flooding ratio for different pressure ratios.

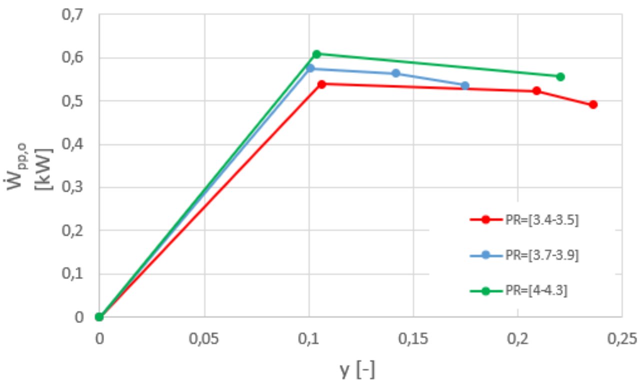

Figure 4: Oil pumping power in function of flooding ratio for different pressure ratios.

Isentropic efficiency also drops with increasing flooding ratio (Fig. 5). The addition of oil thus increases the losses in the expander, instead of decreasing friction and leakage losses. This might be due to an increase in hydraulic losses in the leakage channels for higher oil content [20], or because the tested lubricant oil is not suited for use in refrigeration cycles.
The margin of error on the isothermal efficiency was too large to be able to deduce a clear trend. The temperature ratio however also illustrates how much the process approximates an isothermal process. No observable effect of increasing the flooding on expander outlet temperature was found. Therefore, the potential for internal regeneration also stayed unaltered as well.
Both the cycle and Second Law efficiency decreased with increasing flooding. The trend of ORCLFE efficiency was similar to the one of the net specific power (Fig. 3). This indicates that the increase in heat added to the cycle for heating the oil, is less important compared to the decrease in net power.
Overall, there is an increase in performance for increasing pressure ratios. As pressure ratio increases, it approximates the optimal pressure ratio of the expander (related to the built-in volume ratio). Therefore, over-expansion losses are reduced.
Theoretically, expander and cycle efficiencies should increase and the expansion process should ap-

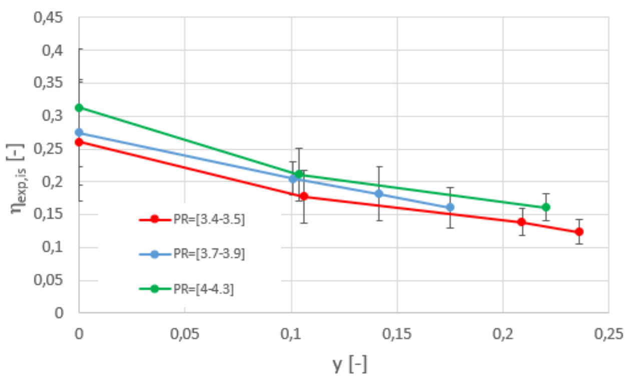

Figure 5: Isentropic efficiency in function of flooding ratio for different pressure ratios.

proximate an isothermal process better when liquid flooding is applied. However, in the limited range of oil fractions tested this effect is not yet seen. In order to make a final conclusion on the impact of oil flooding, additional research is needed. Other oils, which are more suited to be used in refrigeration cycles, should be tested. The limits of the set-up w.r.t. the pressure ratios and control and other performance altering parameters should be investigated. Higher PRs might lead to higher efficiencies as over-expansion losses are reduced, and testing at constant expander inlet pressures eliminates the reduction in power due to pressure decrease. Furthermore, higher flooding ratios should be tested as well. In order to do this, the resonance issue should however be solved first.

5. Conclusion

An organic Rankine cycle is a cycle which can be used for the conversion of low-grade heat sources such as solar, geothermal or waste heat. Modifications to the cycle layout can be done to increase efficiency and power output; applying liquid flooded expansion is one of them. In liquid flooded expansion a large amount of oil is added to the refrigerant before it enters the expander. The oil acts as a thermal buffer, and pushes the expansion process towards an isothermal process. This increases the power output and increases the potential for internal regeneration. In addition, the oil reduces friction and leakage losses in the expander. A test set-up, with a separate oil circulation loop, has been built to experimentally investigate liquid flooded expansion. Measurements are done on a single-screw expander and R1233zd(E) is used as refrigerant. Methods for data reduction and alteration of set-points are developed. Flooding and pressure ratios are varied and different performance parameters are calculated, as well as their uncertainty intervals. In addition, a preliminary experimental investigation was performed. Additional research with a different oil, higher pressure ratios and higher flooding ratios is needed to make a conclusion on the impact of liquid flooding on organic Rankine cycle performance.

Acknowledgments

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Nomenclature

$\dot{m}$	mass flow rate, $\mathrm{kg/s}$
p	pressure, Pa
$\dot{Q}$	heat rate, $\mathrm{J/s}$
T	temperature, K
v	specific volume, $\mathrm{m^3/kg}$

$\dot{W}$ power, $\mathrm{J/s}$

x mass fraction, $-$

y flooding ratio, $-$

Greek symbols

η efficiency

Subscripts and superscripts

exp expander

hf heating fluid

is isentropic

isoth isothermal

o oil

pp pump

r refrigerant

Acronyms

BIVR Built-in volume ratio

LFE Liquid flooded expansion

ORC Organic Rankine cycle

ORCLFE Organic Rankine cycle with liquid flooded expansion

PR Pressure ratio

SSE Single-screw expander

TR Temperature ratio

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