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Employing a Single-Screw Expander in an Organic Rankine Cycle with Liquid Flooded Expansion and Internal Regeneration

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Abstract

Positive displacement expanders are proven to be cost-effective in the low to medium power range for Organic Rankine Cycle (ORC) systems. Among the different types of volumetric expanders, the screw-type presents a favorable combination of relatively high internal volume ratio (up to 7) and isentropic efficiency (up to 80%) with respect to the optimal pressure ratio at which sub-critical ORCs operate. In particular, single-screw expanders have shown some potential due to their symmetric and balanced configuration that decreases the loads on the bearings. A comprehensive characterization of this type of machine with two working fluids, i.e., SES36 and R245fa, has been carried out in a previous work [1]. Based on the experimental work, friction losses and internal leakages were found detrimental to the expander performance. As the expander requires lubrication during operation, flooded expansion can be beneficial to reduce such losses as well as to improve the expansion process toward a quasi-isothermal behavior. A thermodynamic cycle model has been developed to evaluate the potential improvements on the thermodynamic performance of organic Rankine cycle with flooded expansion and internal regeneration. A semi-empirical model of the expander is included which accounts for the effects of internal volume ratio. The results from the cycle model have used to design an ORC test setup with an independent lubricant oil loop and internal regeneration. The new test rig will be used validate the trends obtained with the cycle model and to further characterize the single-screw expander. The working fluid employed is R1233zd(E) as a replacement for R245fa.

Keywords: ORCLFE; Single-screw expander; R245fa; R-1233zd(E);

1. Introduction

Low-grade waste heat recovery (80-200 °C) with organic Rankine cycle (ORC) is a well established solution to effectively generate power. Although a wide range of studies exist that address working fluid selection, cycle archi-

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tectures and expander technologies [2–4], there is still room to improve such system as the current thermodynamic efficiency is usually less than 30% of the corresponding Carnot efficiency.

The expansion process in an ORC is bounded between two limit transformations, i.e. adiabatic expansion and isothermal expansion. Since non-negligible heat transfer occurs during the expansion process in a positive displacement machine, the actual expansion deviates from an adiabatic transformation. Theoretically, approaching an isothermal expansion allows to extract more work.

In the medium to low power range (<150 kW), volumetric-type of expanders are cost effective [3]. In particular, screw-type of expanders can potentially reach isentropic efficiency above 80% [3]. As these machines require active lubrication systems, i.e., dedicated lubrication loops (multi-injection ports), the concept of liquid flooded expansion can be explored to achieve two goals: (i) improve the expansion process toward an isothermal to increase the potential power output and favor the use of internal regeneration; (ii) use the flooding medium (typically lubricant oil) to minimize the friction losses. As a result, organic Rankine cycle with liquid flooded expansion (ORCLFE) and internal regeneration is proposed to investigate such benefits. From previous numerical analyses [5,6], it has been shown how positive displacement expanders with larger internal volume ratios are favored for investigating flooded expansion. For this reason, a single-screw expander is considered to show the potential benefits of ORCLFE for waste heat recovery. The characterization of such expander with R245fa and SES36 without significant amount of lubricant oil has been carried out in [1]. In this work, a cycle model has been developed along with a semi-empirical model of the expander to account for the presence of oil, internal volume ratio, heat and friction losses. The cycle model includes also the effect of lubricant oil and working fluid solubility. As a result of the numerical study, an experimental test setup has been designed and built to assess the benefits of a controlled flooded expansion as well as to compare R245fa and its potential replacement R1233zd(E). Lubricant oil ACD100FY [7] is used as flooding medium.

Nomenclature

a_l	liquid volume fraction, -	T	temperature, °C
h	specific enthalpy, J/kg	w	specific work, J/kg
$\dot{m}$	mass flow rate, kg/s	$\dot{W}$	power, W
N_{exp}	expander rotational speed, rpm	y	flooding ratio, -
p	pressure, Pa	η	thermodynamic efficiency, -
$\dot{Q}$	heat rate, W	ϕ	filling factor, -
r_v	specific volume ratio, -		

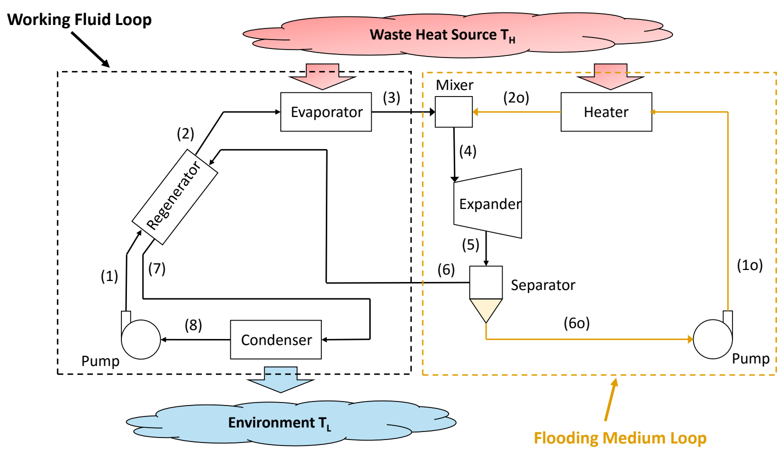


Fig. 1. Schematic of ORCFLE system.

2. ORCLFE system description

By considering the cycle schematic proposed in Figure 1, both the primary working fluid (1) and the flooding medium (1o) are pumped to the high system pressure. While the flooding medium is heated up directly by the heater (2o), the working fluid is first preheated inside the internal regenerator (2) and then vaporized and superheated by the evaporator (3). The finite heat source is used to heat up the primary working fluid and the flooding medium. State (3) and state (2o) are assumed to be at the same temperature and pressure conditions. The two fluids undergo a mixing process (4) prior to entering the expander. In the mixing section, a homogeneous mixture is ideally achieved. After the expansion process occurs (5), the vapor phase of the working fluid is separated from the flooding medium inside a oil separator (6). The working fluid vapor phase is used to regenerate (7) before it is condensed in the condenser (8). The portion of flooding medium separated is then pumped back to the high pressure side and the cycle is repeated. In Fig. 2, the effect of flooded expansion is shown. As the flooding ratio increases, the discharge temperature of the expander is closer to an isothermal. At the same time, the higher discharge temperature allows for internal regeneration which improves the thermodynamic cycle efficiency. A specific work ratio is defined as the ratio of the isothermal work, w_{isoth}, over the adiabatic and reversible work, w_{ad}. By considering the expansion process from state (4) to state (5), the adiabatic reversible specific work for a real gas is calculated as:

$$w_{\rm ad} = h_4 - h_{5,is} = h_4(T_4, p_4) - h_{5,is}(s_5, p_5) \tag{1}$$

with s_5=s_4. Whereas, the isothermal work is obtained by combining First and Second Laws of thermodynamics for an open system under steady-state conditions:

$$w_{\rm isoth} = h_4(T, p_4) - h_5(T, p_5) - T\left[s_4(T, p_4) - s_5(T, p_5)\right] \tag{2}$$

with T=T_4=T_5. The relative improvement of the isothermal expansion with respect to the adiabatic expansion becomes:

$$\Delta_{\rm isoth} = \frac{w_{\rm isoth}}{w_{\rm ad}} - 1 \tag{3}$$

Equation 3 can be plotted for different working fluids and operating conditions of interests. Figure 3(a) shows the specific work improvement for R245fa and R1233zd(E) for an expander inlet temperature of 120 °C. To be noted is that R1233zd(E) led to a higher specific work improvements compared to R245fa under the same working conditions.

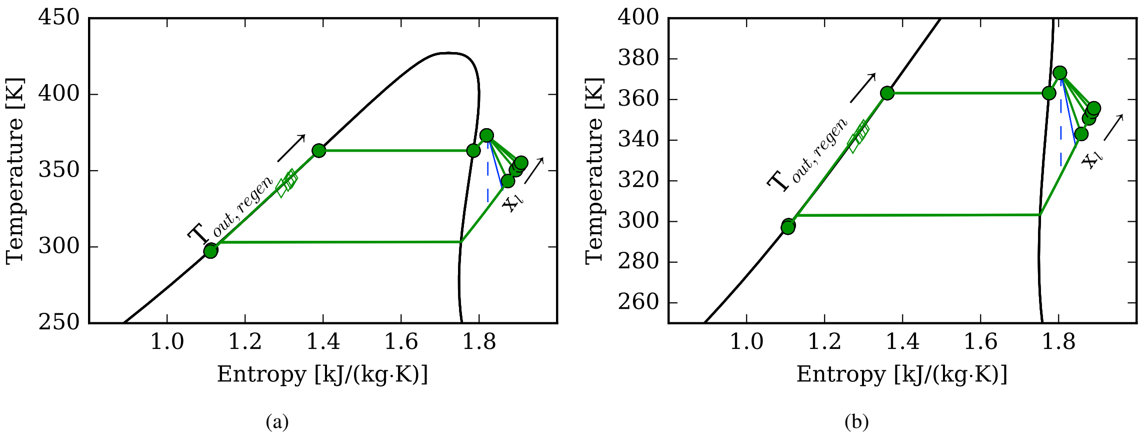


Fig. 2. Thermodynamic plot of ORC with liquid flooded expansion and internal regeneration for different flooding ratios:(*a*) R245fa; (*b*) R1233zd(E).

3. Cycle Modeling

A thermodynamic cycle model has been developed to analyze the ORCLFE system. The assumptions made are listed in Table 1. Real gas properties of the working fluid have been retrived from REFPROP [8]. The lubricant oil has

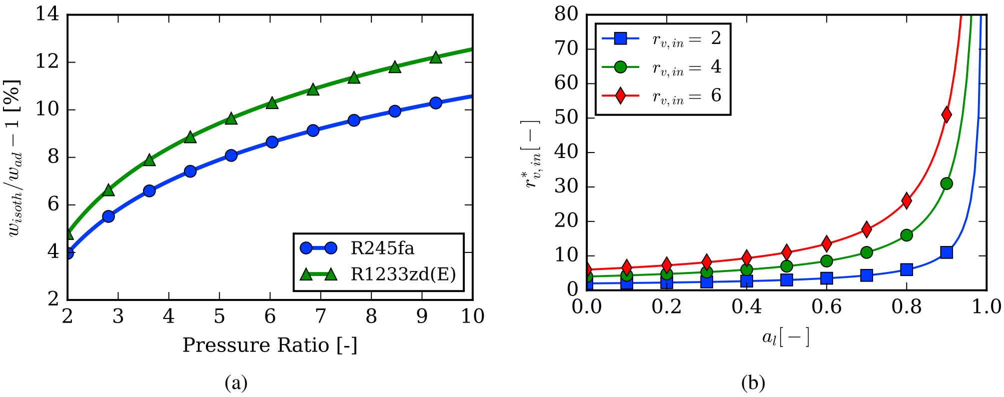


Fig. 3. (*a*) Specific work improvements of an isothermal expansion with respect to an adiabatic expansion; (*b*) Expander effective volume ratios as a function of the flooding medium volume fraction for different geometric built-in volume ratios.

been treated as incompressible and the solubility between refrigerant and oil was considered in the oil separator only in the case of R245fa/ACD100FY since a correlation was available [7]. After the mixing process, oil and refrigerant are assumed to be in thermal and mechanical equilibrium. An oil mass flow ratio is defined as $y_l = \dot{m}_l/\dot{m}_r$, where $\dot{m}_r$ and $\dot{m}_l$ are the mass flow rates of working fluid and lubricant oil, respectively. An ideal mixture model is adopted to estimate the refrigerant-oil mixture properties. The generic mixture thermodynamic property, Ψ_{mix}, such as specific heats, specific enthalpy, specific internal energy, specific exergy, is calculated assuming ideal mixing rule as,

$$\Psi_{mix} = \Psi_r + y_l \Psi_l \tag{4}$$

For the sake of brevity, only the expander model is presented in details in this paper. A detailed description of the thermodynamic cycle model is presented in [6]. A positive displacement expander is characterized by a fixed internal volume ratio, $r_{v,built-in}$, defined as the ratio of the discharge volume of the expansion chamber to the volume of the expansion chamber at suction closure (or the displaced volume), $V_{s,exp}$. Therefore, an effective built-in volume ratio $r^*_{v,built-in}$ [9] can be defined to account for the liquid volume fraction existing in the chamber. It can be demonstrated that the effective volume ratio is given by:

$$r^*_{v,built-in} = \frac{r_{v,built-in} - a_l}{1 - a_l} \tag{5}$$

with $a_l = V_l/V_{s,exp}$ representing the liquid volume fraction in the expander working chamber. It can be noted that as the liquid volume fraction increases, the effective volume ratio increases moderately until approximately 0.8, then more sharply in the range 0.8 - 0.9 and approaching infinity for $a_l \to 1$. This fact is shown in Figure 3(b) where the effective volume ratio is reported as a function of the liquid volume fraction in the working chamber for different geometric built-in volume ratios (2-6). In particular, built-in volume ratios >3.5 are characteristic of screw machines. An expander semi-empirical model is adopted to include the effect of internal volume ratio, mismatch with the applied pressure ratio and the presence of the flooding medium. The internal specific work, i.e., without suction and discharge losses, is expressed as [10]:

$$w_{in,exp} = w_{s,exp} + w_{V,exp} = \left(h_4 - h_{in,exp}\right) + v_{in,exp}\left(p_{in,exp} - p_5\right) \tag{6}$$

where the thermodynamic state *in* is obtained by knowing the internal volume ratio of the expander and by imposing an isentropic expansion step. The theoretical mass flow rate through the expander is calculated as:

$$\dot{m}_{th,exp} = \frac{\dot{V}_{s,exp}}{v_{4,exp}} = \frac{V_{s,exp}}{v_{4,exp}} \frac{N_{exp}}{60} \tag{7}$$

The mass flow rate entering the expander is related to the filling factor, ϕ. It is assumed that the filling factor is unity and therefore $\dot{m}_{exp} = \phi \dot{m}_{th,exp} = \dot{m}_{th,exp}$. Due to the losses during the filling process, it follows that the actual mass flow rate displaced can be expressed as $\dot{m}_{exp} = \dot{m}_{in,exp} + \dot{m}_{leak,exp}$, where $\dot{m}_{in,exp}$ is the internal mass flow rate that produces work and $\dot{m}_{\mathrm{leak,exp}}$ is the lumped leakage flow rate. The expander shaft power is obtained by subtracting the mechanical losses associated with friction and bearing losses to the internal power, i.e. p-V work. A constant mechanical efficiency is introduced to estimate the shaft power:

$$\dot{W}_{\mathrm{sh,exp}} = \dot{W}_{\mathrm{in,exp}}\eta_{\mathrm{mech}} = \dot{m}_{\mathrm{in,exp}} w_{in,exp}\eta_{\mathrm{mech}} \tag{8}$$

where η_{mech} is the expander mechanical efficiency. The expander overall isentropic efficiency, $\eta_{\mathrm{oa,exp}}$, is affected by the pressure ratio across it (i.e., volume ratio - pressure ratio mismatch), by internal leakage losses, by thermodynamic irreversibilities as well as mechanical and friction losses, as outlined by Lemort et al. [10]. The overall isentropic efficiency is calculated as:

$$\eta_{\mathrm{oa,exp}} = \eta_{\mathrm{in}}\eta_{\mathrm{mech}}\eta_{\mathrm{is,th}} = \frac{\dot{W}_{\mathrm{in,exp}}}{\dot{W}_{\mathrm{pV,th,exp}}}\frac{\dot{W}_{\mathrm{sh,exp}}}{\dot{W}_{\mathrm{in,exp}}}\frac{\dot{W}_{\mathrm{pV,th,exp}}}{\dot{W}_{\mathrm{is,th,exp}}} \tag{9}$$

where $\dot{W}_{\mathrm{pV,th,exp}}$ is the theoretical p-V work rate and $\dot{W}_{\mathrm{is,th,exp}}$ is the isentropic work rate. The overall cycle thermodynamic efficiency is given as the ratio of the net power output to the total heat rate input:

$$\eta_{ORCLFE} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{sh,exp} - \dot{W}_{pp,r} - \dot{W}_{pp,l}}{\dot{Q}_{ev,r} + \dot{Q}_{heater,l}} \tag{10}$$

where $\dot{W}_{pp,r}$ and $\dot{W}_{pp,l}$ are the power input for working fluid pump and lubricant oil pump, and $\dot{Q}_{ev,r}$ and $\dot{Q}_{heater,l}$ are the heat rate at the evaporator and oil heater. The pump input power is calculated by assuming a constant isentropic efficiency (see Table 1). A pinch point analysis is implemented to estimate the heat transfer rate in the heat exchangers.

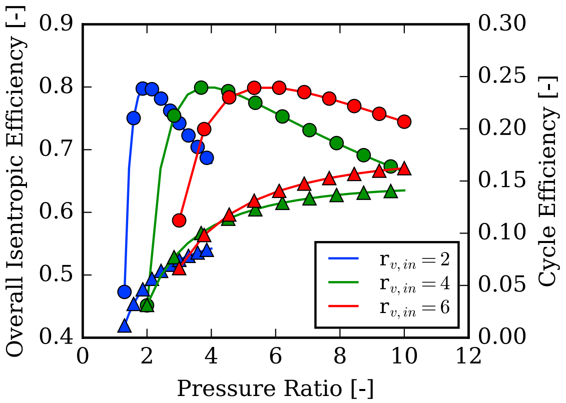


Fig. 4. Influence of the expander built-in volume ratio on overall isentropic efficiency (circle markers) and cycle efficiency (triangle markers) at different pressure ratios with R245fa. The flooding ratio is optimized for each simulation point. Pressure drops at suction and discharge ports of the expander are not considered as they are machine specific.

4. Results and Discussion

The thermodynamic model is used to quantify the theoretical improvement on the expander work output that can be achieved with an isothermal expansion as well as to compare the thermodynamic cycle efficiency of ORCLFE with a conventional ORC with internal regeneration. At first, R245fa is considered as the primarily working fluid. The inlet heat source temperature is fixed at 120 °C. Under the specified conditions, the degrees of freedom are the internal volume ratio of the expander , the evaporating temperature and flooding ratio. As the cycle efficiency strongly depends on the evaporating pressure for given cold sink and hot source conditions, the analysis is extended to account for a range of pressure ratios. The results are shown in Figure 4. By optimizing the flooding ratio at each pressure ratio and expander volume ratio, the higher the pressure ratio the higher the cycle efficiency. Furthermore, on the same plot, it is possible to analyze the effect of the pressure ratio on the expander isentropic efficiency. As the internal volume

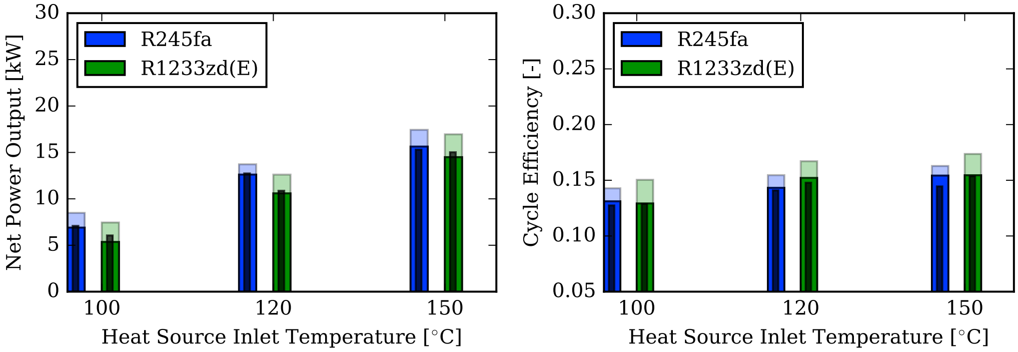
Table 1. List of assumptions made in the cycle and component models.

Description	Value
Condenser outlet subcooling	5 °C
Temperature difference between heat sink and condenser outlet	5 °C
Cold sink temperature	20 °C
Evaporator pinch point temperature difference	5 °C
Heat source temperature	100-150 °C
Heat source mass flow rate	1 kg/s
Flooding ratio	0-1
Regenerator effectiveness (if not specified)	0.9
Pump isentropic efficiency	0.5
Pump electric motor efficiency	0.9
Expander isentropic efficiency	Calculated
Expander mechanical effciency (if not specified)	0.8
Expander ambient heat transfer (UA_{amb})	0.01 kW/(m^2 K)
Negligible pressure drop in linesets, separator, mixer and heat exchangers	-
Negligible heat loss in linesets, separator, mixer, pumps	-

ratio increases, the effect of the under-expansion is less detrimental and the optimized oil flooding ratio increases. The lower volume ratio expander efficiency curve resembles the one from a scroll-type of expander [11]. The curves at higher volume ratios are characteristic of screw-type expanders [1,12]. The cycle model is then exercised to calculate the cycle performance of the ORCLFE for three hot source inlet temperatures of interest, i.e., 100 °C, 120 °C and 150 °C. Degree of superheating, pressure ratio and flooding ratio are optimized to maximize the net power output. The single-screw expander characteristics have been implemented into the cycle model. In particular, internal volume ratio and mechanical losses were accounted for [1,13]. The simulation results are shown in Figure 5 and reported in Table 2. To be noted is that for each working fluid and heat source temperature, three bars are plotted. In particular, the solid bar represents the performance of the ORCLFE, the centered solid black bar indicates the performance of the conventional ORC system with internal regeneration and the shaded bar is representative of the ORCLFE with reduced expander mechanical losses. The flooded-expansion and internal regeneration improved the cycle efficiency with respect to the conventional ORC by as high as 6.71% for R245fa at 150 $^\circ C$. In the case of R1233zd(E), the maximum improvement of 2.90% was obtained at 120 $^\circ C$. Overall, the two working fluids achieved similar cycle performance. However, R1233zd(E) allowed to generate slightly more power output at both 120 $^\circ C$ and 150 $^\circ C$ than R245fa. By reducing the expander mechanical losses due to the presence of a significant amount of lubricant oil, the potential of ORCLFE with screw-type of expander became more clear. In particular, each working fluid showed further improvements between 5.5% (R245fa at 150 °C) and 16.4% (R1233zd(E) at 100 °C) in net power output with respect to the optimized ORCLFE.

5. ORCLFE Test setup

The results from thermodynamic cycle model have been used to design an ORC test rig to evaluate the effects of the liquid-flooded expansion in a single-screw expander and to assess the actual performance improvements with respect to the theoretical results. An overview of ORCLFE system built along with the description of the main components is shown in Figure 6. The experimental test stand can be divided into four main loops (refer to Figure. 1): hot source loop, cold source loop; working fluid loop and active oil circulation loop. Heating and cooling loops are the two main external loops to the ORCLFE. In particular, the heating source loop consists of an electric heater with a maximum heating capacity of 250 kWe. Therminol 66 is employed as thermal oil. A roof-top air cooled condenser is used as cooling loop. The cooling medium is a mixture of water and ethylene-glycol (33 vol%). The temperature of the water-glycol mixture that enters the condenser depends directly on the external ambient conditions. Two three-piston diaphragm pumps are used to pressurize the fluids in both working fluid and lubricant oil loops. The pumps are



(a) (b)

Fig. 5. Optimization of ORCLFE for three heat source inlet temperatures. Deep colored bars represent ORCLFE performance, the shaded bars are the results of ORCLFE with reduced mechanical losses and the black bars are the ORC with internal regeneration results: (*a*) net power output; (*b*) thermodynamic cycle efficiency.

Table 2. Comparison between ORC baseline and optimized ORCLFE for different heat source inlet temperatures.

Fluid	T_H (°C)	y_l (-)	r_p (-)	$\dot{W}_{net}$ (kW)	η_{ORCLFE} (-)
R245fa	100	0.0345	6.146	6.899 (-2.65%)	0.1311 (+2.90%)
	120	0.0082	9.334	12.61 (+1.02%)	0.1432 (+1.63%)
	150	0.2695	12.87	15.63 (+2.15%)	0.1542 (+6.71%)
R1233zd(E)	100	0.1724	6.492	5.356 (-11.58%)	0.1365 (+0.31%)
	120	0.00391	9.236	10.59 (-2.57%)	0.1557 (+2.90%)
	150	0.1462	12.42	14.49 (-3.52%)	0.1633 (+0.58%)

controlled by two ABB variable frequency drives (VFDs). A single-screw expander converted from air-compressor is used as expansion device. The characterization of such machine has been discussed in [1]. From the original expander, only the housing has been kept. Pressure and temperature sensor connections have been drilled through the housing to record the internal expansion process. Main rotor and starwheels have been replaced with an identical but new meshing pair to improve the volumetric efficiency. Furthermore, copper gaskets and stainless steel side plates have been installed to allow higher operating pressures and limit leakages through the housing. The expander shaft power is coupled with a 15 kWe generator. The generator is connected to a regenerative drive and the electrical power is injected into the grid. Plate heat exchangers are employed as evaporator, heater, regenerator and condenser. The mixing between working fluid and lubricant oil is realized by means of a static mixer in stainless-steel. The internal patterns of the mixer have been optimized to minimize the pressure drop. The setup is equipped with temperature and pressure measurements at the inlet and exit of every component except the liquid line between condenser and liquid receiver. Torque sensors are installed on expander and working fluid pump shafts.

6. Conclusions

In this paper, quasi-isothermal expansion and internal regeneration are employed to enhance organic Rankine cycle system performance. Flooded-expansion with screw-type of expanders leads to potentially reduce internal friction

Fig. 6. View of ORCLFE test rig. The main components are indicated and described.

losses as well as increase the cycle efficiency. A cycle model system has been used to compare the performance of R245fa and R1233zd(E) as well as investigate the benefits of flooded expansion in a single-screw expander. A dedicated ORCLFE test rig has been designed and built with the purpose of assessing the effect of liquid-flooded expansion in a single-screw expander and to validate the expected theoretical results.

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