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Online Measurement Of The Working Fluid Mass Repartition In A Small-Scale Organic Rankine Cycle Power System

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ABSTRACT

This paper presents an experimental investigation of the working fluid charge repartition in a 2kWe ORC (organic Rankine cycle) test bench. To this end, an online measurement apparatus is built and fully calibrated to evaluate the charge enclosed in the three heat exchangers and the liquid receiver of the ORC unit. By changing all the system boundary conditions (including the charge enclosed in the test rig), an experimental database of 304 steady-state points is gathered and post-treated. The charge inventories obtained by online measurements demonstrate promising results *on average* but experience high uncertainties when considering each point individually (i.e. the uncertainty on the global inventory is around ± 2.5 kg for a total charge of 31.2 kg). Deviations of the evaporator mass measurements are identified at high temperature of the heat source and discussed in details. A reconciliation method is applied to the raw measurements in order to retrieve consistent charge inventories while accounting for the different sources of uncertainty. Ultimately, the paper analyses the impact of increasing the charge in the ORC and how this parameter influences the thermodynamic state of the system.

1. INTRODUCTION

A common aspect of organic Rankine cycle (ORC) power systems is the versatile nature of their operating conditions. Once sized and built, ORC engines are often led to work in off-design conditions because of changes in their operating environment (e.g. of the heat source, heat sink, electrical load, ambient temperature, etc.). In order to properly understand (and, by extension, to properly simulate) the off-design performance of such systems, both the energy *and* the mass balances of the various components must be taken into account. Besides the energy transfers, one must account for the total charge of fluid in the system and how it is spread through the components in function of the operating conditions. The charge-sensitive modelling of ORC system is a new topic of research and a few papers have been published in this field over the last two years. However, the existing works are either purely theoretical (Liu et al., 2017; Pan et al., 2018) or partially validated from a charge's point of view (Dickes et al., 2018, 2017b; Ziviani et al., 2016). In order to provide a better validation, experimental measurements of the charge repartition in the cycle are mandatory and such investigations have only been performed for vapor injection and HVAC systems (Björk, 2005; Jin and Hrnjak, 2016; Li et al., 2015; Peuker, 2010).

Since the late 80's, different charge measurement methods have been developed and most of the published works used a *quick-closing valve* approach (Ding et al., 2009). In this method, the system is divided in different sections and, once the mass measurement is desired, actuated valves are quickly closed in order to trap the refrigerant in the various cycle sections. From then, different methods can be used to withdraw the fluid from each section and to weigh it so as to reconstruct the system charge inventory. If properly executed, such a technique offers a high result accuracy, but it requires to stop and to discharge the system for every single mass measurement. On the opposite, another approach is to directly weigh the components by hanging them to a load cell. This technique, known as *online measurement method*, allows a continuous recording of the fluid mass repartition without interfering the system operation. Despite offering a lower measurement accuracy (Grodent, 1998), this approach is not intrusive and offers two key advantages:

1. Dynamic charge recording can be performed during transient operations.
2. Wider range of conditions can be investigated in a least amount of time.

Because of these important advantages, an online measurement method is chosen to conduct this work. To the best of the author's knowledge, this research project constitutes the first attempt to experimentally investigate the working fluid mass repartition in an organic Rankine cycle.

The paper is structured as follows: the test rig, the acquisition system and the mechanical apparatus built to measure the components weight are firstly described in Section 2. The experimental campaign conducted with the ORC unit is briefly presented in Section 3. Finally, Section 4 discusses the reliability of charge measurements obtained for the entire system and analyses the impact of the charge on the thermodynamic behavior of the unit.

2. SYSTEM DESCRIPTION

2.1 Architecture and components

To conduct this work, a small-scale recuperative ORC unit is investigated as case study. Depicted in Figure 1, the system has a nominal power output of $2kW_e$ and employs HFC-R245fa as working fluid (WF). The heat source is an electrical boiler and thermal oil *Pirobloc Basic* is used as heat transfer fluid (HTF). Brazed plate heat exchangers are used for both the evaporator and the recuperator while an air-cooled fin coil heat exchanger is used for the condenser. The system includes a liquid receiver at the condenser outlet and a filter/dryer in the pump exhaust line. The fluid is pressurized with a single-diaphragm pump and is expanded through a hermetic scroll expander. In order to mitigate vibrations through the system, both mechanical components are installed on silent block bushes and connected to the cycle with anti-vibration hoses. The pump and the condenser fan are controlled by variable-frequency drives, while the expander speed is set by controlling its electrical load (i.e. variable resistances). In order to limit heat transfers to the ambient, all the components and the piping are thermally insulated. More details about the system components can be found in previous reports (Dickes et al., 2017a).

2.2 Measurements and acquisition

The test rig is fully monitored to record the ORC performance. T-type thermocouples and piezoresisitve pressure transducers are located at each key location of the system (see Figure 1). Flow rates of the working fluid and the thermal oil are measured with a Coriolis flow meter and a standard multi-jet flow meter, respectively. The air stream across the condenser was previously correlated to the fan frequency using an anemometer (Dickes et al., 2014).

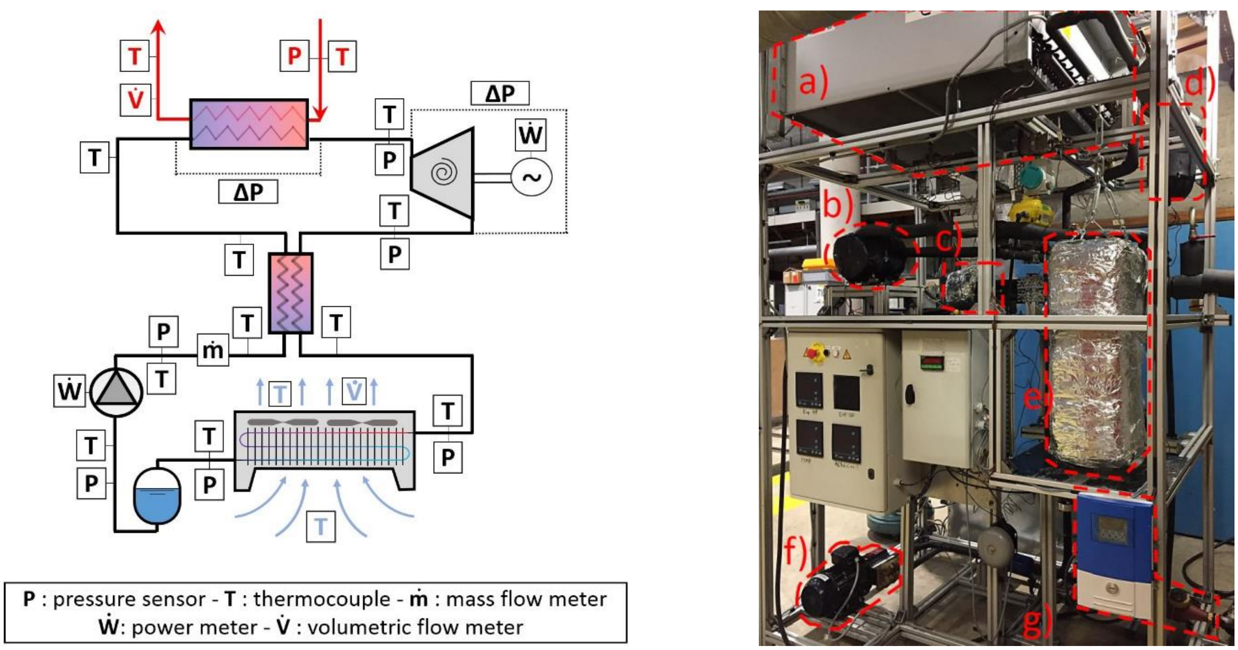


Figure 1: *Left*: Scheme of the 2kWe ORC test rig. *Right*: photo of the system: (a) Condenser (b) Expander (c) Recuperator (d) Liquid receiver (e) Evaporator (f) Diaphragm pump (g) Flow meters.

Besides these standard measurements, the test rig allows the recording of the fluid charge through the ORC system. Because of the little contributions of the mechanical components in the charge inventory, only the three exchangers and the liquid receiver are monitored using an online measurement technique. Using this method, each of the four components is suspended and weighted by a bending load cell as depicted in Figure 2. These elements are then connected to the rest of the circuit using flexible anti-vibration hoses. In order to mechanically isolate the suspended components from the rest of the system (and thus to least influence the mass measurements), the extremity of each flexible hose is firmly held to the test bench structure with holding clamps. For example, the apparatus built for weighting the recuperator is depicted in Figure 3.

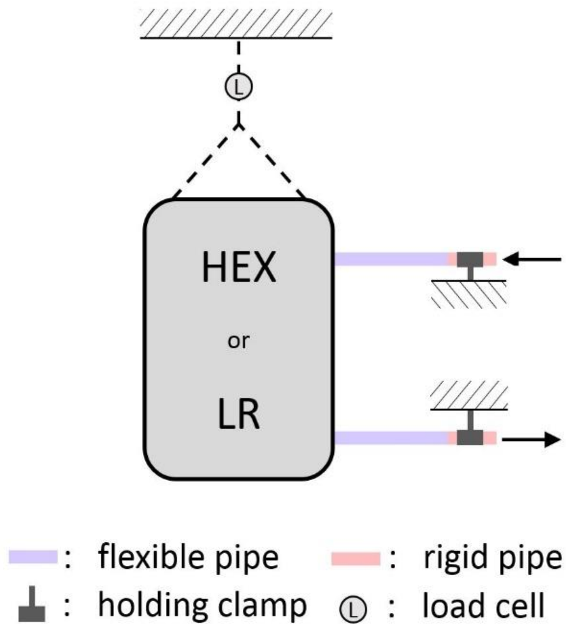


Figure 2: Mechanical structure of the online measurement method for recording the charge in a component.

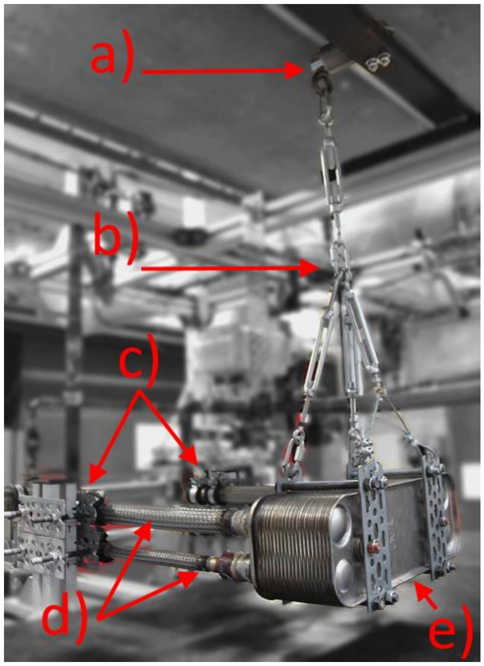


Figure 3: Apparatus built for the recuperator before thermal insulation. (a) load cell (b) hanging structure (c) holding clamps (d) flexible hoses (e) recuperator.

The raw measurements of the load cells cannot be used alone to retrieve the mass enclosed in the components. Indeed, the pressure inside the flexible hoses influences the system mechanical behavior and impacts the apparent weight seen by the force transducers. To account for this effect, a dedicated calibration is applied for the three heat exchangers and the liquid receiver. Once installed and thermally insulated, references weights are attached under each of the four components and the load cells signals are recorded for different pressure levels in the system (controlled by injecting nitrogen in the test bench). The pressures and reference masses tested in the calibration are chosen to cover the entire range of experimental conditions met by each component. Using these calibration data, triangulation-based interpolants are fitted to correlate the load cells signals and the operating pressures to the actual mass enclosed in each component. The influence of the operating temperatures on the mass measurement is neglected because of its presumed negligible impact. This simplified assumption appears to be wrong for the evaporator as further discussed in Section 4.

Like for the other sensors (pressures, temperatures, powers and flow rates), the load cells signals are collected by a NI compactRio and displayed in real-time through LabView interface. After the experiments, the raw measurement are exported and post-treated in Matlab using CoolProp as thermos-physical library (Bell et al., 2014). Further details about the measurements sensors and the acquisition systems are given in Table 1.

Table 1: Details of the acquisition system and the sensors.

Variables	Sensor details	Final accuracy
Temperatures	T-type thermocouple	± 0.5°C
Pressures	Piezoresistive sensors (21Y Keller)	± 1.5% FS
WF mass flow rate	Optimass 7300C Coriolis flowmeter	± 0.5% meas.
HTF mass flow rate	MTWH multijet flow meter	± 5% meas.
Expander power	PQ-Box 100 wattmeter	± 0.5% meas.
Pump power	A2000 Gossen wattmeter	± 0.5% FS
Fan power	A2000 Gossen wattmeter	± 0.5% FS
Evaporator mass	250 kg Tedea Huntleigh load cell	± 1% meas.
Recuperator mass	50 kg Tedea Huntleigh load cell	± 1% meas.
Liquid receiver mass	50 kg Tedea Huntleigh load cell	± 1% meas.
Condenser mass	250 kg Tedea Huntleigh load cell	± 1% meas.

3. EXPERIMENTAL CAMPAIGN

Using the test rig, an experimental campaign is conducted and a set of 304 steady-state points is gathered as reference database. Steady-state performance points are obtained by averaging the raw measurements over 10-minute periods in stabilized conditions (i.e. situations without any deviation in the system state). Such a long time window is chosen to minimize the impact of noise disrupting the load cells signals. The tests are performed without following any dedicated control strategy for the ORC. Instead, the behavior of the test bench is investigated over extended ranges of conditions, including part-load and non-optimal performance points.

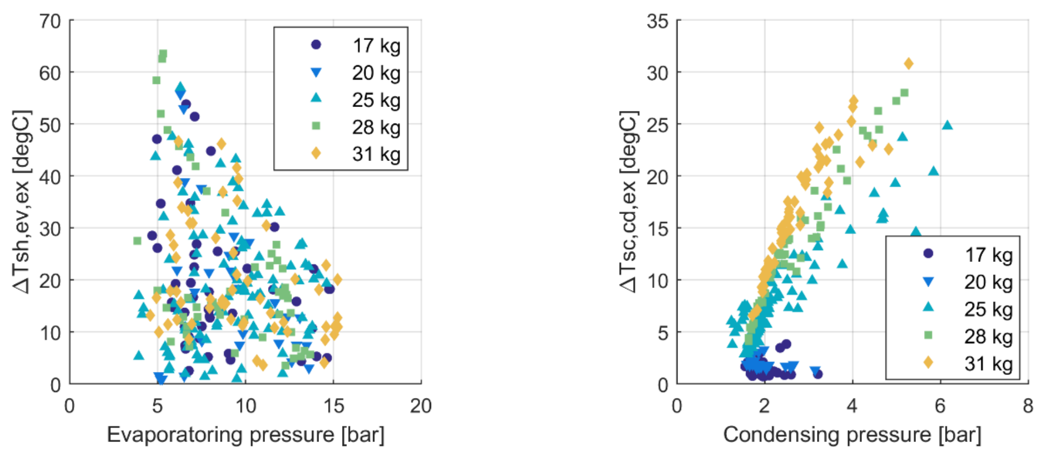


Figure 4: Outlook of the temperature profiles tested experimentally in the evaporator (exhaust superheating vs. evaporating pressure) and in the condenser (exhaust subcooling vs. condensing pressure). Each marker color corresponds to a specific charge of R245fa.

As depicted in Figure 4, various temperature profiles are explored in the heat exchangers in order to induce significant fluid migration through the system. To this end, all the system boundary conditions are changed, including the total refrigerant charge enclosed in the ORC unit. Ultimately, five different charges of working fluid are tested (16.6 kg, 19.6 kg, 25 kg, 28 kg and 31.2 kg) while keeping constant the amount of lubricating oil in the circuit (1.5 kg). A summary of the operating conditions covered by the experimental database is given in Table 2.

Table 2: Range of conditions covered by the experimental database.

Variable	Min.	Max.	Unit
$\dot{V}_{htf,su}$	0.05	1.2	l/s
$T_{htf,su}$	66	150	°C
T_{amb}	12	26	°C
P_{ev}	3.8	15.3	bar
P_{cd}	1.2	6.2	bar
$\dot{m}_{wf}$	23	117	g/s
$\dot{W}_{exp}$	105	1875	W
$\eta_{net,ORC}$	-2.7	6	%
M_{R245fa}	16.6	31.2	kg
M_{oil}	1.5 (constant)	1.5 (constant)	kg

4. RESULTS AND DISCUSSION

Post-treatments of the raw measurements demonstrate consistent energy balances for the different components as well as a good redundancy between the various flow, pressure and temperature transducers. The load cells measurements are analyzed by confronting the observed charge inventories in the ORC to the actual amounts of fluids enclosed in the test rig. In Figure 5, each bar represents the charge inventory through the system for a point of the experimental database (304 in total). As described in Section 2, masses in the heat exchangers and the liquid receiver are directly monitored with calibrated load cells. For the remaining of the system (i.e. in the pipes and the mechanical components), masses are computed using the sections geometry and the fluid density at the local thermodynamic conditions (i.e. using the T/P measurements). The blue and the red dashed lines in Figure 5 represent the actual charge of fluid in the system with and without accounting for the lubricating oil. The green dashed line, on the other hand, represents the mean value of total mass recorded in the system for each set of charge.

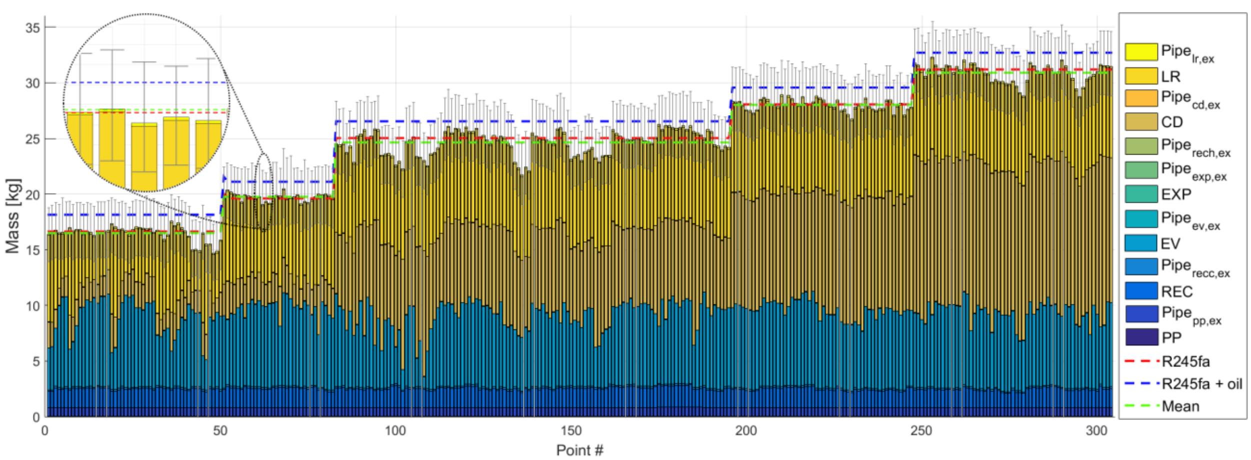


Figure 5: Experimental measurement of the fluid repartition in the ORC unit.

These results demonstrate the ability of the online measurement technique to record variations of charge in the test bench. For each set of charge (from 16.6 kg to 31.2 kg), the mean value of total mass recorded in the system matches closely the effective amount of R245fa in the ORC. The deviation between the green and the red lines is 246.8 g on average, which correspond to a relative error of 0.8 % (resp. 1.4 %) for a charge of 31.2 kg (resp. 16.6 kg). The measurements fit better the charge of pure refrigerant than the charge accounting for the lubricant. The reason comes out the assumption made in computing the fluid density in the unweighed sections of the system. For a preliminary analysis, the density in the pipes and the mechanical components is calculated assuming pure R245fa as working fluid (i.e. without oil contamination). A more detailed model of the R245fa/oil mixture flowing through the system is under development and will help to better match the effective charge in the system (i.e. the green and the blue lines).

Although precise in average, the total mass monitored for an individual point is subjected to significant uncertainties (± 2.5 kg). Indeed, each charge inventory relies on many sensors measurements, all characterized by a limited accuracy, which results in a large uncertainty propagation. If the charge of pure refrigerant is taken as reference (i.e. the red line in Figure 5), the mean error committed by the global charge measurement is 680 g over the entire database. In most cases, the deviations between the measured charge inventory and the actual amount of fluid remain lower than the measurements uncertainty. For some points, however, significant offsets are recorded (up to 3.3 kg) and they cannot be justified solely by the measurements inaccuracy.

More specifically, all the points experiencing prohibitive deviations appear when high-temperature HTF flows in the evaporator. In order to better understand the behavior of the evaporator's load cell in such conditions, additional tests are performed on this component only. To this end, a given amount of fluid is enclosed in the evaporator and confined by closing the valves at the inlet and outlet of the heat exchanger. The mass of fluid remaining constant in the evaporator, the temperature of the oil is changed step-by-step while recording the mass as detected by the load cell. This process is repeated for different set of conditions to ensure a good repeatability and the results are depicted in Figure 6.

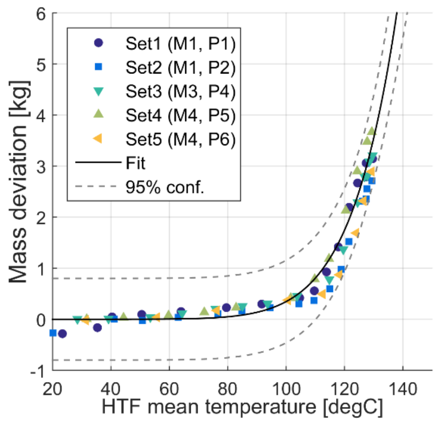


Figure 6: Deviations in the mass measurement of the evaporator load cells in function of the HTF temperature

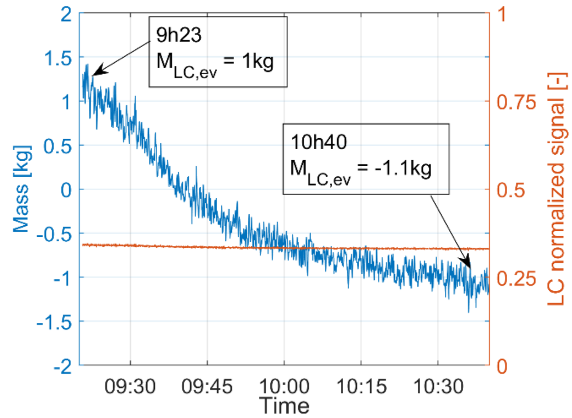


Figure 7: Profiles of the load cell signal (orange) and the recorded mass (blue) during a 2-hour test while keeping constant the mass and all the operating conditions of the evaporator.

Unexpectedly, a significant deviation of the mass measurement appears at temperatures higher than 115°C. Over 130°C, the load cell measurement can underpredict down to 4 kg the actual mass enclosed in the evaporator. The same trend is observed for each set of tests and corroborates well the offsets observed in the experimental database. These deviations result from an intrinsic problem of the online measurement method: because of the weight of the component (M_{ev} = 100 kg), a large-scale load cell (0-250 kg) is required to ultimately measure a small amount of fluid. As depicted in Figure 7, even if the temperature does not significantly impact the mechanical structure of the system (i.e. thermal expansions < 1mm) and its absolute influence on the load cell signal remain small, the WF mass observation may be highly affected. The initial assumption that the operating temperature does not impact the load cell measurement in the evaporator proves to be wrong. The other components, however, are less subjected to this problem because of their lower operating temperatures. More surprisingly, the effect of the temperature is not immediate. In the situation depicted in Figure 7, the load cell signal took over 2h to stabilize while all the operating conditions related to the evaporator were kept stable (i.e. no change of $T_{htf}, P_{htf}, T_{wf}, P_{wf}$ and $\dot{V}_{htf}$). Because of this dynamic effect, the actual offset corrupting the evaporator measurement is not only function of the oil temperature, but it also depends of the system thermal history. Therefore, the deviations depicted in Figure 6 cannot be used blindly to correct the evaporator charge measurements. Instead, they rather provide an upper bound of the offset that could be induced by high HTF temperatures.

In order to retrieve a consistent charge inventory through the ORC while exploiting all the aforementioned results, a reconciliation method is applied to the charge measurements (Dumont et al., 2015). The goal of the reconciliation is to correct the raw measurements - as little as possible and within the sensors accuracy range - in order to respect the actual charge in the test bench. Mathematically, it can be formulated as the definition of corrected measured values c_i which minimize a penalty function $f(c_i)$, i.e.

$$\min_{c_i} f(c_i) = \sum_{i=1} \frac{|r_i - c_i|^2}{\sigma_i} \tag{1}$$

while imposing the global charge constraint, i.e.

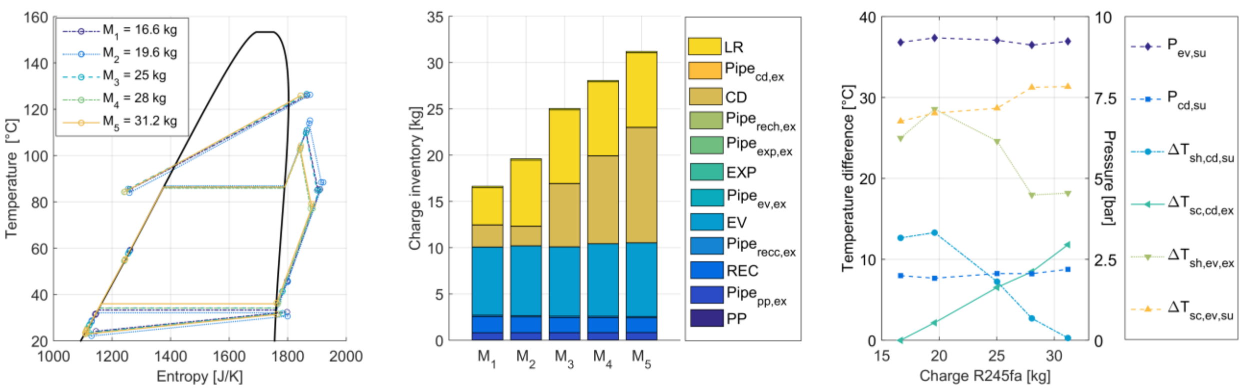
$$\sum_{j=1} M_j(\bar{c}) = M_{exp} \tag{2}$$

were r_i represent the original measurements (e.g. the temperature, pressure or load cell signal), σ_i are the sensor accuracies, M_j is the mass in the jth component and M_{exp} is the experimental charge in the test rig. This method allows to account for the increasing uncertainty of the evaporator measurement at high HTF temperature, i.e.

$$M_{ev,rec} \in [M_{ev,raw} - \sigma_{ev}\ ;\ M_{ev,raw} + \sigma_{ev} + \Delta M_{ev}] \tag{3}$$

where $M_{ev,rec}$ is the evaporator reconciliated mass measurement, $M_{ev,raw}$ is the evaporator raw mass measurement, σ_{ev} is the uncertainty due to the limited sensors accuracy and, finally, ΔM_{ev} is a function that fits the deviations depicted in Figure 6.

This constrained optimization is applied to the 304 points of the experimental database. For example, Figure 8 depicts the results gathered after post-treatment for five different conditions. These five points show the impacts of increasing the charge of working fluid (from M1 = 16.6 kg to M5 = 31.2 kg) while keeping the other boundary conditions as constant as possible.



a) b) c)

Figure 8: Experimental results obtained after reconciliation for five points for which the mass is increased and the other boundary conditions are kept constant. (a) T-s diagrams (b) charge inventories (c) subcooling/superheating/pressure of the evaporator and the condenser.

At charge M1, the liquid receiver is partially filled (LR ~30% filled) and a saturated liquid flow leaves the condenser. When increasing the charge from 16.6 kg to 19.6 kg, the additional amount of fluid (i.e. 3 kg) is absorbed by the liquid receiver, which starts being flooded. When increasing the charge over 20kg (from M2 to M5), the liquid receiver cannot absorb any additional fluid and the excess of charge is spread to the heat exchangers. The condenser is the main absorber and thus the most impacted. As the charge in the system is increased, the condenser becomes more and more filled by liquid, which is highlighted by a modification of its inner temperature profile. As depicted in Figure 8c, the fluid superheating at the condenser inlet falls from 14 K to 0.5 K while its outlet subcooling rises from 0 K to 12 K. Besides these changes of temperature profiles, the condensing pressure is increased as well (from 1.9 bar to 2.2 bar between M2 to M5). For the conditions investigated here, the mass in the recuperator is not much influenced because only a vapor phase flows on the hot side. However, if the mass in the system was kept increasing (i.e. up to

36 kg), a two-phase region would have appeared in the recuperator hot stream, resulting in a rise of its enclosed charge. The evaporator contributes much less to absorb the additional amount of working fluid. Like the condenser - but at a lower scale - the evaporator becomes more filled by liquid (decrease of $\Delta T_{sh,ev,ex}$ and increase of $\Delta T_{sc,ev,su}$) but the evaporating pressure is not significantly influenced by the charge in the system. By affecting the ORC thermodynamic state, and mainly its condensing pressure, the charge of working fluid also impacts the system conversion performance. The net power output of the test rig decreases from 630 W to 520 W when increasing the charge from 16.6 kg to 31.2 kg. The net system efficiency follows the same trend with a drop from 4.83% to 3.94%. Besides of the economical benefit to minimize the amount of fluid in an ORC system, it also allows to increase the system thermodynamic performance. However, to decrease the charge of fluid limits the off-design flexibility of the unit and may lead to control issues in transient operations (e.g. cavitation of the pump). Such discussions go beyond the scope of the current paper but it highlights the open questions that are still to be explored in this topic.

5. CONCLUSIONS

This paper presents the results of an experimental investigation of the fluid repartition in a 2kWe recuperative ORC unit. The main outcomes of the study can be summarized as follows:

- A 2kWe ORC test bench has been built and fully instrumented to measure both the thermal performance and the fluid repartition inside the system.
- An online measurement technique is used to evaluate the charge enclosed in the three heat exchangers and the liquid receiver. The mass in the rest of the system is obtained knowing the sections geometry and the density at the local thermodynamic state.
- A dedicated calibration of the load cells signals is performed to account for the impact of the operating pressure on the mass measurements.
- An experimental campaign is conducted with the test bench by changing all the system boundary conditions, including the charge enclosed in the ORC unit. In total, 304 steady-state points are gathered.
- The online measurement method demonstrates promising results *on average*, but experiences high uncertainty when considering each point individually. In most cases, the deviations between the measured charge inventory and the actual amount of fluid remain lower than the measurements uncertainty (± 2.5kg). At high HTF temperature, however, significant offsets are observed.
- The impact of the HTF temperature on the evaporator's load cell measurement cannot be neglected and is investigated in details. Over 130°C, under-estimation of the evaporator mass can exceed 4 kg. More surprisingly, the impact of the HTF temperature is not immediate and there is a dynamic long-term response of the system (the evaporator load cell signal can take up to 2 hours to stabilize during warm-up procedures).
- A reconciliation method is proposed to retrieve consistent charge inventories in the test bench while accounting for the uncertainty of the evaporator mass measurements.
- These new data permit to better understand the evolution of the thermodynamic state of the ORC when increasing the charge and open rooms to many new investigations.

Prospective works include to exploit these charge measurements to fully validate charge-sensitive models already developed by the authors (Dickes et al., 2018). Indeed, these new measurements provide precious information to characterize the heat transfer coefficients and the two-phase void fractions characterizing the various heat exchangers in the system.

ACKNOWLEDGMENT

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NOMENCLATURE

Acronyms		**Subscripts**	
CD	Condenser	amb	ambient
EV	Evaporator	cd	condenser
EXP	Expander	ev	evaporator
HEX	Heat Exchanger	ex	exhaust
HTF	Heat Transfer Fluid	exp	expander
LC	Load Cell	rec	reconciliated
LR	Liquid Receiver	sc	subcooling
ORC	Organic Rankine Cycle	sh	superheating
PP	Pump	su	supply
REC	Recuperator		
WF	Working Fluid		

Variables

c	Reconciliated meas.	(-)
M	Mass	(kg)
P	Pressure	(bar)
R	Raw measurement	(-)
T	Temperature	(°C)
$\dot{m}$	Mass flow	(kg/s)
$\dot{V}$	Volume flow	(m^3/s)
$\dot{W}$	Power	(W)
Δ	Difference	(-)
η	Efficiency	(%)
σ	Accuracy	(-)

REFERENCES

Bell, I.H., Wronski, J., Quoilin, S., Lemort, V., 2014. Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library coolprop. Ind. Eng. Chem. Res. 53, 2498–2508.

Björk, E., 2005. A simple technique for refrigerant mass measurement. Appl. Therm. Eng. 25, 1115–1125. doi:10.1016/j.applthermaleng.2004.09.008

Dickes, R., Dumont, O., Daccord, R., Quoilin, S., Lemort, V., 2017a. Modelling of organic Rankine cycle power systems in off-design conditions: an experimentally-validated comparative study. Energy 123, 710–727. doi:10.1016/j.energy.2017.01.130

Dickes, R., Dumont, O., Declaye, S., Quoilin, S., Bell, I., Lemort, V., 2014. Experimental investigation of an ORC system for a micro-solar power plant, in: Proceedings of the 22nd International Compressor Engineering at Purdue. Purdue (USA).

Dickes, R., Dumont, O., Quoilin, S., Lemort, V., 2018. Charge-sensitive modelling of organic Rankine cycle power systems for off-design performance simulation. Appl. Energy 212, 1262–1281. doi:10.1016/j.apenergy.2018.01.004

Dickes, R., Guillaume, L., Dumont, O., Quoilin, S., Lemort, V., 2017b. Effects of void fraction and heat transfer correlations in a charge-sensitive ORC model – a comparison with experimental data, in: Proceedings of ECOS 2017. pp. 1–13.

Ding, G., Ma, X., Zhang, P., Han, W., Kasahara, S., Yamaguchi, T., 2009. Practical methods for measuring refrigerant mass distribution inside refrigeration system. Int. J. Refrig. 32, 327–334. doi:10.1016/j.ijrefrig.2008.05.002

Dumont, O., Quoilin, S., Lemort, V., 2015. Importance of the reconciliation method to handle experimental data : application to a reversible heat pump / organic Rankine cycle unit integrated in a positive energy building. Int. J. Energy Environ. Eng. doi:10.1007/s40095-016-0206-4

Grodent, M., 1998. Contribution à l'étude des composants de systèmes frigorifiques: modélisation en régime stationnaire et validation expérimentale. Application des modèles développés à l'étude d'un système "bisplit." University à Liège.

Jin, S., Hrnjak, P., 2016. Refrigerant and lubricant charge in air condition heat exchangers: Experimentally validated model. Int. J. Refrig. 67, 395–407. doi:10.1016/j.ijrefrig.2016.01.002

Li, T., Lu, J., Chen, L., He, D., Qiu, X., Li, H., Liu, Z., 2015. Measurement of refrigerant mass distribution within a R290 split air conditioner. Int. J. Refrig. 57, 163–172. doi:10.1016/j.ijrefrig.2015.05.012

Liu, L., Zhu, T., Ma, J., 2017. Working fluid charge oriented off-design modeling of a small scale Organic Rankine Cycle system. Energy Convers. Manag. 148, 944–953. doi:10.1016/j.enconman.2017.06.009

Pan, Y., Liu, L., Zhu, T., 2018. Simulation of working fluid mass distribution in small-scale Organic Rankine Cycle system under sub-critical conditions. Appl. Therm. Eng. 131, 884–896. doi:10.1016/j.applthermaleng.2017.12.017

Peuker, S., 2010. Experimental and analytical investigation of refrigerant and lubricant migration. University of Illinois at Urbana-Champaign.

Ziviani, D., Woodland, B., Georges, E., Groll, E., Braun, J., Horton, W., van den Broek, M., De Paepe, M., 2016. Development and a Validation of a Charge Sensitive Organic Rankine Cycle (ORC) Simulation Tool. Energies 9, 389. doi:10.3390/en9060389