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# An experimental analysis of flow boiling and pressure drop in a brazed plate heat exchanger for organic Rankine cycle power systems

Adriano Desideri [a],*, Ji Zhang [b], Martin Ryhl Kærn [b], Torben Schmidt Ommen [b], Jorrit Wronski [c], Vincent Lemort [a], Fredrik Haglind [b]

[a] Thermodynamics Laboratory, University of Liège, Campus du Sart Tilman, B49, B-4000 Liège, Belgium
[b] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 403, 2800 Kongens Lyngby, Denmark
[c] IPU, Kongens Lyngby, Denmark

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ABSTRACT

Organic Rankine cycle power systems for low quality waste heat recovery applications can play a major role in achieving targets of increasing industrial processes efficiency and thus reducing the emissions of greenhouse gases. Low capacity organic Rankine cycle systems are equipped with brazed plate heat exchangers which allows for efficient heat transfer with a compact design. Accurate heat transfer correlations characterizing these devices are required from the design phase to the development of model-based control strategies. In this paper, the experimental heat transfer coefficient and pressure drop during vaporization at typical temperatures for low quality waste heat recovery organic Rankine cycle systems are presented for the working fluids HFC-245fa and HFO-1233zd. The experiments were carried out at saturation temperatures of 100 °C, 115 °C and 130 °C and inlet and outlet qualities ranging between 0.1–0.4 and 0.5–1 respectively. The experimental heat transfer coefficients and frictional pressure drop were compared with well-known correlations and new ones are developed. The results indicated weak sensitivity of the heat transfer coefficients to the saturation temperature and were characterized by similar values for the two fluids. The frictional pressure drop showed a linear dependence with mean quality and increased as the saturation temperature decreased.

## 1. Introduction

In recent years, the consensus over anthropogenic climate change [1–3] as well as the rising prices for heat and electricity [4] are driving a global transition towards a green energy based economy. Furthermore, as a result of electricity sector liberalization polices, undertaken by several countries worldwide [5], distributed generation solutions are experiencing a significant growth [6]. In this context, many studies have underlined the potential of waste heat recovery from industrial processes in reducing both energy costs and associated emissions [7,8]. In particular, it has been shown that a significant amount of the available industrial waste heat is at low temperature (<200 °C) which makes it difficult to harvest [9–11]. Among the available technologies for low quality waste heat recovery (WHR), organic Rankine cycle (ORC) power systems have been proven to be a viable solution in the large power capacity range, say from hundreds of kW to a few MW [12,13]. In recent years, there has been an increasing interest for investigating the potential of small scale ORC units for low temperature WHR, say from few kW to tens of kW [14–16]. Due to the non-constant nature of the wasted thermal energy available from industrial facilities, a specific control strategy ensuring safe and optimal operation of the ORC unit in any conditions are required. Before a control system can be designed the dynamic behavior of the ORC unit needs to be well investigated [17,18]. As the thermal inertia of the heat exchangers determines the characteristic transients of the power unit [19], specific heat transfer coefficient correlations play a fundamental role in the model accuracy.

In an ORC power system, the evaporator design and heat transfer performance plays a major role for the overall system efficiency. An effective evaporating heat transfer leads to higher expander inlet temperature and thus better cycle efficiency. Validated evaporation heat transfer correlations for ORC systems are therefore necessary from the early design stage to the development and testing of efficient model-based control strategies. Despite the broad use of brazed plate heat exchangers (BPHX) for small ORC systems, the available literature covering the performance of these devices at the typical evaporation temperatures

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* Corresponding author.
*E-mail address:* adesideri@ulg.ac.be (A. Desideri).

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## Nomenclature

*Acronyms*

| | |
|---|---|
| HFC | hydrofluorocarbon |
| HFO | hydrofluoroolefin |
| WHR | waste heat recovery |
| ORC | organic Rankine cycle |
| HX | heat exchanger |
| BPHX | brazed plate heat exchanger |
| TC | thermocouple |
| PT | pressure transmitter |
| DPS | differential pressure sensor |
| CFM | Coriolis flow meter |
| TFM | turbine flow meter |
| MFM | magnetic flow meter |
| AV | automatic valve |
| MV | manual valve |
| R | refrigerant |

*Subscripts*

| | |
|---|---|
| su | supply |
| ex | exit |
| wf | working fluid |
| hf | hot fluid |
| wat | water |
| eva | evaporator |
| meas | measured |
| m | mean |
| p | plate |
| ch | channel |
| v | saturated vapor |
| l | saturated liquid |
| vap | vaporization |

*Symbols*

| | |
|---|---|
| $p$ | pressure (bar) |
| $T$ | temperature (°C) |
| $\rho$ | density (kg m$^{-3}$) |
| $\mu$ | viscosity (Pa s) |
| $k$ | thermal conductivity (W m$^{-1}$ k$^{-1}$) |
| $h$ | specific enthalpy (J kg$^{-1}$) |
| $\alpha$ | fluid heat transfer coeff. (W m$^{-2}$ k$^{-1}$) |
| $U$ | overall heat transfer coeff. (W m$^{-2}$ k$^{-1}$) |
| $\dot{Q}$ | thermal power (W) |
| $\dot{q}$ | thermal flux (W m$^{-2}$) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$) |
| $G$ | mass flux (kg s$^{-1}$ m$^{-2}$) |
| $c_p$ | specific heat capacity (J kg$^{-1}$ K$^{-1}$) |
| $X$ | vapor quality (–) |
| $l_p$ | wall thickness (m) |
| $d_h$ | hydraulic diameter (m) |
| $Re$ | Reynolds number (–) |
| $Pr$ | Prandtl number (–) |
| $We$ | Weber number (–) |
| $Bo$ | boiling number (–) |
| $Bd$ | Bond number (–) |
| $Nu$ | Nusselt number (–) |

of ORC power units for low quality WHR is scarce [20] and no heat transfer correlations for high temperature evaporation exist [21]. Most of the literature reporting heat transfer characteristics for plate heat exchangers with non-conventional fluids are related to the refrigeration field where the vaporization conditions are far from the ones characterizing ORC power units.

It is generally accepted by the scientific community to consider the nucleate and convective heat transfer phenomena as the two main drivers in thermal energy transfer during evaporation [22]. Three main approaches taking into account the two boiling effects have been developed in the past, namely the superposition, the asymptotic and the enhancement model [23,24]. Although these approaches have been originally developed for in-tube flow boiling, they are often used in plate heat exchangers experiments by adjusting the empirical coefficients to fit the experimental data [21]. Since their invention in the late 19th century, plate heat exchangers have been subject to scientific investigation. In 1981, Danilova et al. [25] presented one of the first flow boiling study on a plate heat exchanger with refrigerants HFC-12, HFC-22, HFC-113 and ammonia. A linear dependence between heat transfer coefficient and vapor quality and mass flux was shown. In 1995, Thonon et al. [26] proposed a method to identify the transition between the two boiling regimes and suggested that the nucleate phenomenon is expected to dominate over the evaporation heat transfer at high pressures.

In the last two decades, the innovative brazing manufacturing process allowed raising the efficiency and lowering the costs. The increasing interest of brazed plate heat exchangers led to significant experimental work to characterize their performances during flow boiling. Yan and Lin [27] and Hsieh and Lin [28] experimentally investigated the evaporation heat transfer and frictional pressure drop of HFC-134a during saturated flow boiling in a vertical plate heat exchanger. The effect of saturation temperature, heat flux, mass flux and vapor quality was analyzed. Flow visualization through a transparent outlet plate showed that the flow remained turbulent also at very low Reynolds number. Empirical correlations for the heat transfer coefficient and the frictional pressure drop as a function of the Reynolds and the Boiling number were presented. A correlation based on the superposition method for predicting flow boiling data of HFC-410a was later presented by Hsieh and Lin [29]. Han et al. [30] performed an experimental investigation on HFC-410a and HFC-22 during flow boiling in brazed plate heat exchangers. The effect of different chevron angle was analyzed at different mass fluxes, operating pressures, vapor qualities and the heat fluxes. Empirical correlations based on the ones developed by Hsieh and Lin [28] were derived by including a term accounting for the different geometries. Palm et al. [31] studied the experimental single and two-phase heat transfer coefficients in brazed plate heat exchangers for HFC-22 and HFC-134a. Their results support the Thonon assumptions, furthermore they found that the Cooper pool boiling correlation [32] well correlated the experimental data. Longo et al. [33] presented experimental data for HFC-134a, 410a and 236fa vaporization inside BPHX at typical evaporation temperature for traditional heat pump applications. The experimental heat transfer coefficients resulted well predicted by the Cooper [32] and Gorenflo [34] correlations for HFC-134a, 410a and slightly under-predicted for 236fa, indicating that the nucleate boiling phenomena controlled the vaporization of HFC-134a and 410a, while HFC-236fa was influenced by convective boiling. Linear dependency of the frictional pressure drop to the kinetic energy per unit of volume was found. In a later study, isobutane, propane and propylene vaprization inside brazed plate heat exchanger was investigated [35] for different heat fluxes, mass fluxes, operating pressures and vapor inlet and outlet conditions. Also in this case a linear dependence of the frictional pressure drop with the kinetic energy per unit of volume was