Proceedings of the 10th World Congress on Momentum, Heat and Mass Transfer (MHMT 2025)
Barcelona, Spain - April, 2025
Paper No. ICMFHT 132
DOI: 10.11159/icmfht25.132

An Experimental Setup to Validate Flow Boiling Heat Transfer Correlations in Horizontal Circular Tubes

Rodrigo C. Branco[1], João S. Pereira [1], José B. Ribeiro [1]
[1]*Univ Coimbra, ADAI*
Department of Mechanical Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal
rodrigo.branco@adai.pt; joao.pereira@dem.uc.pt;jose.baranda@dem.uc.pt

Abstract **-** Two-phase flow boiling is a fundamental principle in thermal systems. Its high heat transfer coefficient values and its importance during the phase change processes are vital for refrigeration and power generation systems such as Organic Rankine Cycles (ORC). Accurate prediction of the flow boiling heat transfer coefficient (h_{tp}) is critical to the design of heat exchangers (HEX) and to ensure reliable operation. The existing correlations for flow boiling in horizontal, circular, smooth tubes have been primarily validated for hydrofluorocarbon (HFC) and hydrocarbon (HC) fluids used in refrigeration systems. However, it should be noted that ORC systems operate under distinct conditions, specifically with higher temperatures, heat fluxes, and larger diameters, causing a shift in the heat transfer dynamics. Additionally, the focus of the current studies with experimental data is connected to HFCs, which are soon to be phased out due to their high global warming potential (GWP), highlighting the need for updated validation in the ORC range of applicability with low-GWP alternatives, such as hydrofluorolefins (HFO). To address these challenges, the development of an experimental setup capable of measuring the h_{tp} under a wide range of ORC-relevant operating conditions and fluids is essential. Such a setup would allow the validation of existing correlations, their fundamental understanding, and the development of new ones targeted to ORC systems. Therefore, this study provides valuable design guidelines and discussions on the development of this experimental setup, such as a novel method to obtain high-quality images of two-phase flow boiling, which is essential to identify flow patterns and study heat transfer mechanisms accurately.

Keywords**:** Rankine; Evaporator, Flow boiling; Two-phase flow; Flow pattern.

1. INTRODUCTION

Two-phase flow boiling or condensing, either due to high values of the heat transfer coefficient, exceeding by an order of magnitude that of single flow [1], or due to the importance of phase change phenomena in the operating principles of thermodynamic machines, is widely used in various industrial applications, whether they relate to refrigeration or power generation systems [2].

In this context, the development of correlations to determine the two-phase flow boiling heat transfer coefficient (h_{tp}) is crucial. This coefficient is essential for the heat exchanger design because its accurate prediction provides a detailed understanding of HEX performance, which is particularly important in scenarios involving sensitive factors such as thermal degradation [3].

However, the available scientific knowledge does not yet allow the h_{tp} to be determined from first physical principles, requiring the use of semi-empirical correlations. These correlations, often calibrated for specific operating conditions, exhibit significant deviations when applied outside their validation range [4]. This limitation arises due to the complexity of two-phase flow boiling compared to the single-phase flow, which involves different flow patterns, each associated with a different evolution of the h_{tp} as long as the fluid evaporates [5].

Current flow boiling correlations are primarily developed for horizontal circular smooth tubes in refrigeration applications, targeting operating conditions typical of micro/mini tubes [6]. However, Organic Rankine Cycle (ORC) systems, which are critical for converting low-enthalpy heat sources into power [7], operate under higher temperatures, heat fluxes, and larger tube diameters [8]. Consequently, the heat transfer dynamics shift, leading to inaccuracies in existing correlations and poor predictive capabilities [9]. Therefore, the available data for the domain of validation of ORC systems is significantly more limited. Furthermore, most experimental ORC-oriented studies focus on R245fa [10], a widely used hydrofluorocarbon (HFC) in ORC systems, which will soon be phased out due to its high global warming potential (GWP) [11]. Low-GWP alternatives, such as hydrofluoroolefins (HFOs) like R1233zd(E) and R1234ze(E), lack sufficient validation for flow boiling correlations in ORC conditions [12]. With this in mind, it is crucial to identify the two-phase flow boiling heat transfer challenges in the ORC range of applicability to help build more comprehensive and precise correlations, improving the reliability of the heat exchangers' design.

To address these challenges, the development of an experimental setup capable of measuring the h_{tp} under a wide range of ORC-relevant operating conditions and fluids is essential. Such a setup would allow the validation of existing correlations, their fundamental understanding and improvement, and the development of new correlations specific to ORC systems. Therefore, the present study provides valuable design insights and discussions for developing these experimental setups, giving a special focus on the visualization section. In this section, the flow pattern during the two-phase state is analyzed. Consequently, its design and construction are crucial to obtaining reliable and high-quality images of the boiling process, enabling an explicit characterization of the two-phase flow heat transfer mechanism.

2. METHODOLOGY AND METHODS

Given the lack of two-phase flow boiling studies towards the ORC range of applicability, an experimental setup, depicted in Fig. 1, has been designed. This setup is capable of obtaining the experimental h_{tp} for a wide range of operating conditions and fluids within the scope of ORC systems.

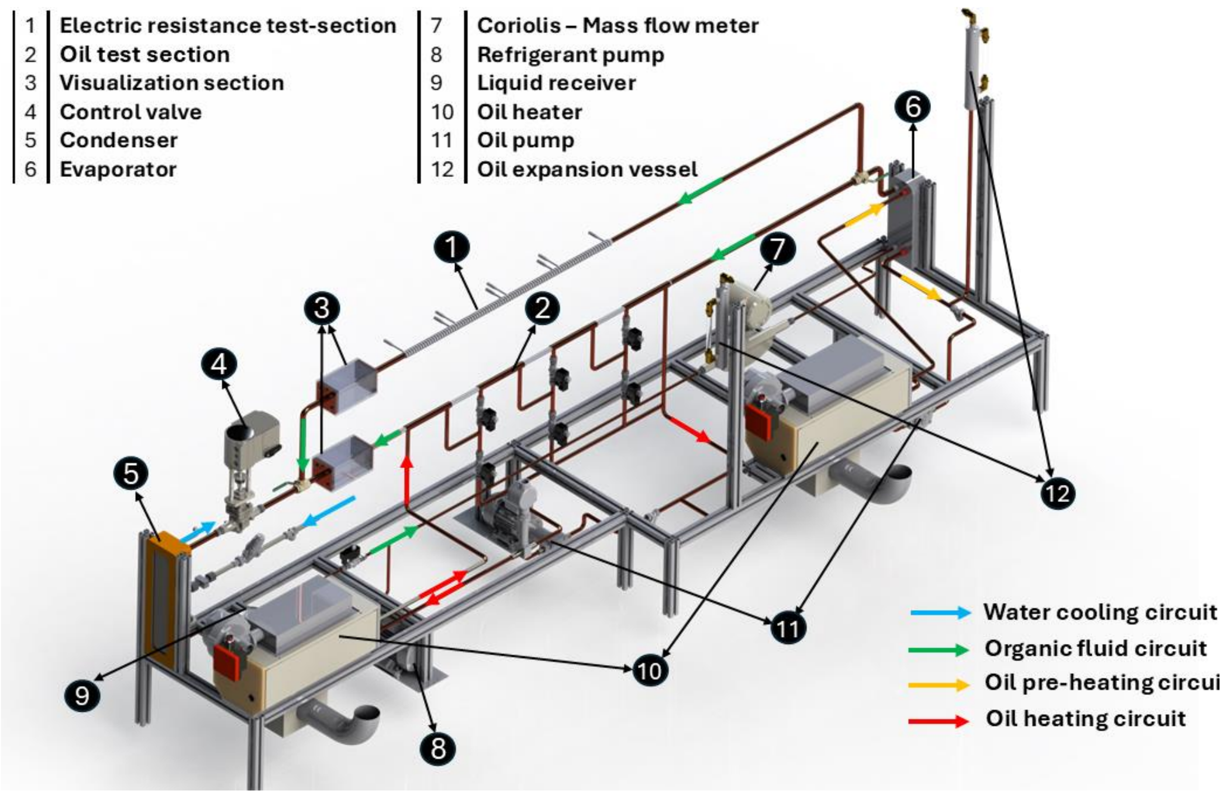

Fig. 1: A schematic design of the experimental setup to measure the h_{tp} of organic fluids during the boiling process.

The experimental setup comprises a primary circuit with the organic fluid, two auxiliary oil circuits, and a water circuit. One auxiliary oil circuit heats the refrigerant to its saturation temperature (T_{sat}), while the other maintains heating during the h_{tp} measurement in the oil test section. Using oil instead of water to heat the refrigerant allows the setup to achieve T_{sat} values up to 150°C, covering most of the ORC applicability range [13]. Moreover, the setup also enables h_{tp} measurements using an electrically heated test section, allowing for investigating both heating methods and their influence on h_{tp} results. The comparison between the results obtained with an oil heater and an electrical heater is of vast interest since the wall temperatures of the tube are entirely different, influencing the organic fluid flow. However, this important aspect is not deeply analyzed in this manuscript. The last circuit, using water, is the cold source of the system, returning the organic fluid to the compressed liquid state.

One of the key features of this experimental setup is its visualization section, which is specifically designed to observe and identify flow patterns and study the heat transfer mechanisms of two-phase flow boiling. This capability is critical to better understand the relationship between flow dynamics and heat transfer performance, which is vital for developing more accurate correlations [14]. Since the quality of flow pattern observation directly impacts the reliability of these studies, capturing high-quality images becomes indispensable.

To guarantee that the images captured in the experimental setup are of optimal quality, exploring and implementing techniques that enhance image clarity and precision is necessary. To this end, an experiment, depicted in Fig. 2, was performed to visualize the flow boiling of water through a horizontal, circular, smooth glass tube.

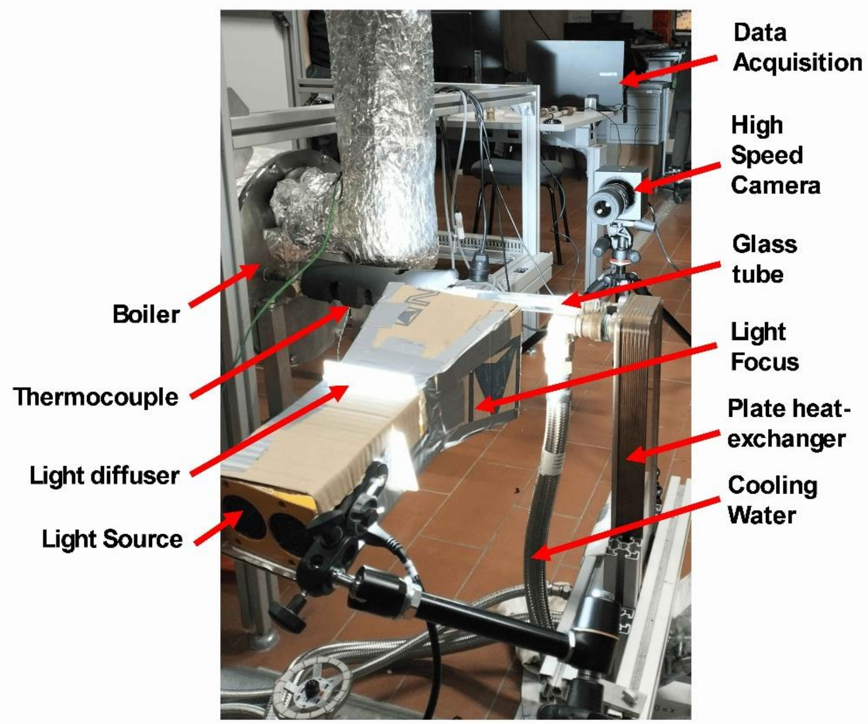

Fig. 2: Two-phase flow boiling visualization experiment.

The experiment was conducted using an open-loop system, where water from the grid was fed into a boiler and heated to its boiling point. A horizontal, circular, smooth glass tube was connected at the boiler's outlet, allowing the visualization of the flow boiling process. A plate heat exchanger was installed downstream of the glass tube to cool the hot water. Cooling was achieved using a separate water connection from the network, ensuring the water could be safely discharged into the sewage system.

Detailed images of the flow boiling phenomena were acquired through a Photron Mini UX high-speed camera with a Sigma 105 mm lens. The delivery of sufficient illumination was assured by the strategic placement of a light source, equipped with a light diffuser, in alignment with the camera lens [14].

The initial raw images captured at different shutter frequencies, as shown in Fig. 3 (A) and (B), revealed suboptimal quality due to uneven lighting. The glass tube acted as a convergent lens, concentrating light in the central section and omitting valuable information from the surrounding areas.

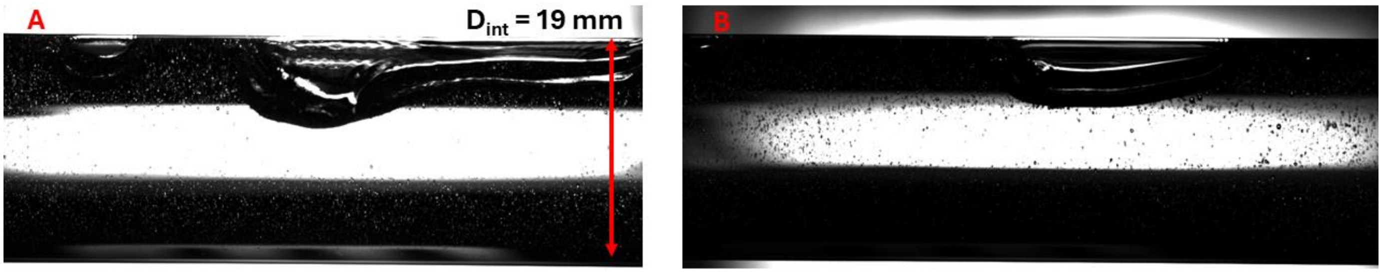

Fig. 3: Flow boiling of water images captured at 3200 fps, shutter frequency of 16 kHz, 1280x512px (A), and at 3200 fps, shutter frequency of 64 kHz, 1280x512px (B).

Therefore, to cancel the effect of the convergence caused by the glass tube, a divergent lens was developed to cancel its effect, as schematically represented in Fig. 4. The divergent lens, printed by a resin 3D printer Creality-SKY, is also shown in Fig. 4.

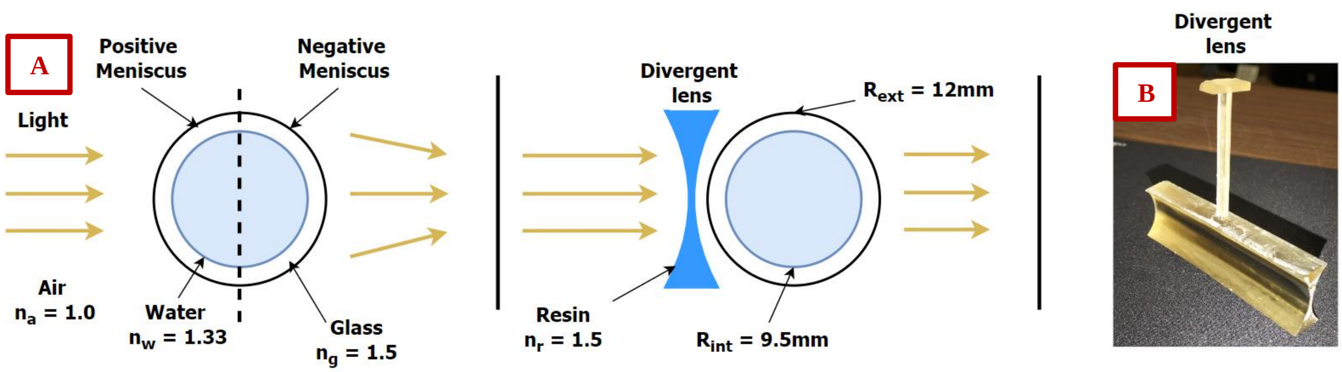

Fig. 4: Schematic illustration of the convergent lens effect of the glass tube causing uneven light distribution and the corrective action of a divergent lens achieving uniform illumination (A); the resin divergent lens (B).

To determine the radius of the divergent lens, the light rays must be traced from the light source to their exit from the water-filled glass tube. This calculation assumes that the collimated light emitted by the source sequentially passes through four distinct optical interfaces. First, the light transitions from air into the divergent lens made of resin, followed by its exit back into the air. Next, the light enters the glass tube, forming a positive meniscus, before reaching the water. Within the tube, the light traverses a column of water, which acts as a second lens. Finally, the light transitions from water back into the glass and then into the air, forming a negative meniscus.

The matrix method for thick lenses was employed to model the entire optical system [15]. Using this approach, the matrices for the positive meniscus, M_p, the water column, M_w, the positive meniscus, M_n, and divergent lens, M_{div}, are derived, as shown in Eqs. (1) - (5).

$$M_p = \begin{bmatrix} 1 & 0 \\ \dfrac{n_g - n_w}{n_w R_{int}} & \dfrac{n_g}{n_w} \end{bmatrix} \times \begin{bmatrix} 1 & t_g \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \dfrac{n_a - n_g}{n_g R_{ext}} & \dfrac{n_a}{n_g} \end{bmatrix} \quad (1)$$

$$M_w = \begin{bmatrix} 1 & t_w \\ 0 & 1 \end{bmatrix} \quad (2)$$

$$M_n = \begin{bmatrix} 1 & 0 \\ \dfrac{n_g - n_a}{n_a(-R_{ext})} & \dfrac{n_g}{n_a} \end{bmatrix} \times \begin{bmatrix} 1 & t_g \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \dfrac{n_w - n_g}{n_g(-R_{int})} & \dfrac{n_w}{n_g} \end{bmatrix} \quad (3)$$

$$M_{div} = \begin{bmatrix} 1 & t_a \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{n_r - n_a}{n_a(R_{div})} & \frac{n_r}{n_a} \end{bmatrix} \times \begin{bmatrix} 1 & t_r \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{n_a - n_r}{n_r(-R_{div})} & \frac{n_a}{n_r} \end{bmatrix} \quad (4)$$

Where, R_{ext} [mm], R_{int} [mm], R_{div} [mm], are the external radius, internal radius, and the divergent lens radius, respectively, t_a [mm], t_g [mm], t_w [mm], t_r [mm], are the travelling distances of the light rays through the air, glass, water, and resin, respectively, and n_r [-], n_g [-], n_w [-], and n_a [-] are the refraction indexes of resin, glass, water and air, respectively.

The individual matrices are applied sequentially, corresponding to the order in which the optical actions affect the light ray as it traverses the system. Therefore, the ray-transfer matrix for the complete optical system, M_{tot}, is calculated as shown with Eq. (5).

$$M_{tot} = M_{div} \times M_p \times M_w \times M_n \quad (5)$$

To determine R_{div}, Eq. (6) is applied with the condition that each ray that enters in the optical system with a certain height (y_0) with an angle ($\alpha_0 = 0$) remains collimated at the exit of the optical system ($y_f = y_0$, $\alpha_f = \alpha_0$) [15].

$$\begin{bmatrix} y_f \\ \alpha_f \end{bmatrix} = M_{tot} \times \begin{bmatrix} y_0 \\ \alpha_0 \end{bmatrix} \quad (6)$$

Using this iterative method and considering a biconcave divergent lens positioned next to the water-filled glass tube, R_{div} was found to be 14 mm.

3. RESULTS AND DISCUSSION

Fig. 5 (A) and (B) show the images captured using the divergent lens at different shutter speeds. The application of the lens effectively prevents the light from concentrating in the middle plane of the glass tube, making the large vapor plugs and slugs clearly visible. However, the top and bottom of the tube remain partially obscured, indicating that the divergent lens does not entirely neutralize the light convergence. This limitation could indicate the need to refine the calculations for R_{div} to achieve optimal results.

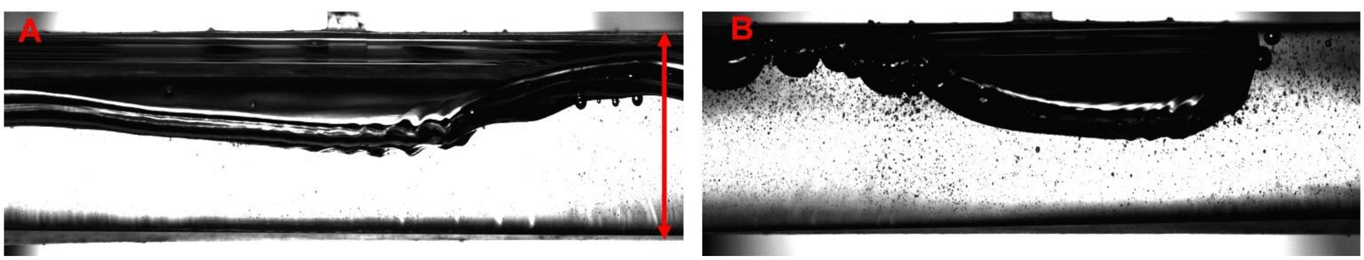

Fig. 5: Flow boiling of water images captured at 3200 fps, shutter frequency of 16 kHz and 1280x512px (A) and at 3200 fps, shutter frequency of 64 kHz and 1280x512px (B) with a resin symmetric divergent lens.

Additionally, several factors related to the resin divergent lens may contribute to these challenges. As the lens is 3D-printed, its refractive index may not be entirely uniform, leading to inconsistencies in light refraction. Furthermore, the lens requires surface treatment to ensure transparency and polishing to minimize irregularities. Despite these efforts, the surface is not entirely smooth, potentially causing light distortions affecting the captured image quality. However, it is important to note that the use of 3D-printed resin lenses significantly reduces costs compared to acquiring custom-made glass lenses with optimal dimensions, making this approach a cost-effective solution for experimental applications requiring rapid prototyping and iterative design.

It is also evident that the light intensity remains higher than desired. This is apparent from the fact that, even as the shutter speed is increased, entrained bubbles in the flow boiling of water become visible, yet excessive light intensity causes significant loss of detail, compromising the ability to capture fine details within the flow structure.

4. CONCLUSION

ORC systems are vital for harnessing low-enthalpy heat sources, making their efficient design and operation a significant research focus. A key challenge is accurately capturing the h_{tp} under ORC-relevant conditions to improve heat exchanger performance and deepen understanding of flow boiling mechanisms.

In order to address these questions, an experimental setup was designed to measure the h_{tp} and visualize the flow boiling phenomena, ensuring a robust foundation for advancing flow boiling knowledge. Particular attention was given to the visualization section, recognizing its critical role in capturing high-quality images of the boiling process. Therefore, an experiment was conducted to optimize the imaging system to visualize the two-phase flow boiling of water in a glass tube. Initial results revealed challenges caused by the glass tube's lensing effect, which distorted the light distribution and reduced image quality. A 3D-printed resin divergent lens was developed as a cost-effective solution to counteract the convergent effect of the glass tube, enhancing illumination uniformity. While the resin lens effectively mitigated some issues, its inherent limitations - such as surface irregularities and potential variations in refractive index - highlight the need for further refinement. Despite these challenges, the study demonstrated the importance of iterative design and experimental optimization in achieving reliable and reproducible results in two-phase flow boiling studies.

Ultimately, this work underscores the critical role of experimental techniques in advancing flow boiling research. By improving imaging quality and addressing design challenges, this study provides valuable insights for future experimental setups, contributing to the development of more accurate flow boiling correlations and enhancing the reliability of ORC system designs.

Acknowledgments

In association with the authors’ host institutions, this research was also supported by the Portuguese Recovery and Resilience Plan (PRR) and Next Generation European Funds EU through the project AM2R with the reference 7253 and by the Agenda Transform project n.º C644865735-00000007, by the European Regional Development Fund (ERDF) of the European Union through the Innovation and Digital Transition Program (COMPETE 2030) of Portugal 2030 under the contract COMPETE2030-FEDER-00591900 and by national funds through FCT – Fundação para a Ciência e a Tecnologia, under the project UIDB/50022/2020, DOI: 10.54499/UIDB/50022/2020 [16]. The financial support is gratefully acknowledged.

References

[1] A.T. Martin, J. Dirker, Influence of different circumferential heat flux distributions on flow boiling of R245fa in a circular horizontal tube, Appl Therm Eng 239 (2024). https://doi.org/10.1016/j.applthermaleng.2023.122071.

[2] M.H. Mousa, C.M. Yang, K. Nawaz, N. Miljkovic, Review of heat transfer enhancement techniques in two-phase flows for highly efficient and sustainable cooling, Renewable and Sustainable Energy Reviews 155 (2022). https://doi.org/10.1016/j.rser.2021.111896.

[3] J.S. Pereira, M. Santos, R. Mendes, J.C. André, J.B. Ribeiro, Thermal degradation assessment study of a direct vaporization ORC based micro-CHP system under close-to-real operating conditions, Appl Therm Eng 214 (2022). https://doi.org/10.1016/j.applthermaleng.2022.118878.

[4] X. Fang, F. Zhuang, C. Chen, Q. Wu, Y. Chen, Y. Chen, Y. He, Saturated flow boiling heat transfer: review and assessment of prediction methods, Heat and Mass Transfer/Waerme- Und Stoffuebertragung 55 (2019) 197–222. https://doi.org/10.1007/s00231-018-2432-1.

[5] N. Kattan, J.R. Thome, D. Favrat, Flow Boiling in Horizontal Tubes: Part 1-Development of a Diabatic Two-Phase Flow Pattern Map, 1998. http://heattransfer.asmedigitalcollection.asme.org/.

[6] S.M. Kim, I. Mudawar, Review of databases and predictive methods for heat transfer in condensing and boiling mini/micro-channel flows, Int J Heat Mass Transf 77 (2014) 627–652. https://doi.org/10.1016/j.ijheatmasstransfer.2014.05.036.

[7] J.S. Pereira, J.B. Ribeiro, R. Mendes, G.C. Vaz, J.C. André, ORC based micro-cogeneration systems for residential application - A state of the art review and current challenges, Renewable and Sustainable Energy Reviews 92 (2018) 728–743. https://doi.org/10.1016/j.rser.2018.04.039.

[8] J.S. Pereira, J.B. Ribeiro, R. Mendes, J.C. André, Analysis of a hybrid (topping/bottoming) ORC based CHP configuration integrating a new evaporator design concept for residential applications, Appl Therm Eng 160 (2019). https://doi.org/10.1016/j.applthermaleng.2019.113984.

[9] D.B. Marchetto, D.C. Moreira, R. Revellin, G. Ribatski, A state-of-the-art review on flow boiling at high reduced pressures, Int J Heat Mass Transf 193 (2022). https://doi.org/10.1016/j.ijheatmasstransfer.2022.122951.

[10] A. Kaya, S. Lecompte, M. De Paepe, Experimental Flow Boiling Study of R245fa at High Reduced Pressures in a Large Diameter Horizontal Tube, Energies (Basel) 15 (2022). https://doi.org/10.3390/en15030864.

[11] M.O. McLinden, J.S. Brown, R. Brignoli, A.F. Kazakov, P.A. Domanski, Limited options for low-global-warming-potential refrigerants, Nat Commun 8 (2017). https://doi.org/10.1038/ncomms14476.

[12] L. Lin, L. Gao, M.A. Kedzierski, Y. Hwang, A general model for flow boiling heat transfer in microfin tubes based on a new neural network architecture, Energy and AI 8 (2022). https://doi.org/10.1016/j.egyai.2022.100151.

[13] M. Jiménez-Arreola, C. Wieland, A. Romagnoli, Direct vs indirect evaporation in Organic Rankine Cycle (ORC) systems: A comparison of the dynamic behavior for waste heat recovery of engine exhaust, Appl Energy 242 (2019) 439–452. https://doi.org/10.1016/j.apenergy.2019.03.011.

[14] H.R. Moran, D. Zogg, V. Voulgaropoulos, W.J. Van den Bergh, J. Dirker, J.P. Meyer, O.K. Matar, C.N. Markides, An experimental study of the thermohydraulic characteristics of flow boiling in horizontal pipes: Linking spatiotemporally resolved and integral measurements, Appl Therm Eng 194 (2021). https://doi.org/10.1016/j.applthermaleng.2021.117085.

[15] S.J. Frank L. Perdrotti, Leno M. Pedrotti, Leno S. Pedrotti, Introduction to Optics, in: Third Edition, Cambridge University Press, Cambridge, 2017. https://doi.org/10.1017/9781108552493.

[16] Laboratório Associado de Energia Transportes e Aeronáutica. (17/01/2025), Available: https://sciproj.ptcris.pt/en/157684UID, (2025). https://doi.org/10.54499/UIDB/50022/2020.