COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-2023
EXPERIMENTAL EVALUATION OF A PLATE-TYPE HEAT EXCHANGER USING THE THERMOSYPHON'S PRINCIPLE

Victor Vaurek Dimbarre
Federal University of Technology - Parana (UTFPR), Department of Mechanical Engineering, Av. Dr. Washington Subtil Chueire, 330, Jardim Carvalho, 84.017-220, Ponta Grossa, PR, Brazil
victordimbarre@alunos.utfpr.edu.br

Felipe Mercês Biglia
Federal University of Technology - Parana (UTFPR), Department of Mechanical Engineering, St. Deputado Heitor Alencar Furtado, 5000, Ecoville, 81.280-340, Curitiba, PR, Brazil
biglia@alunos.utfpr.edu.br

Allefe Chagas Vaz
Federal University of Technology - Parana (UTFPR), Department of Mechanical Engineering, Av. Dr. Washington Subtil Chueire, 330, Jardim Carvalho, 84.017-220, Ponta Grossa, PR, Brazil
allefevaz@alunos.utfpr.edu.br

Paulo Henrique Dias dos Santos
Federal University of Paraiba (UFPB), Department of Mechanical Engineering, University City, 58.051-900, João Pessoa, PB, Brazil
profpaulosantosct@gmail.com

Thiago Antonini Alves
Federal University of Technology - Parana (UTFPR), Department of Mechanical Engineering, Av. Dr. Washington Subtil Chueire, 330, Jardim Carvalho, 84.017-220, Ponta Grossa, PR, Brazil
antonini@utfpr.edu.br

Abstract. *Thermal and energy efficiencies are essential in various industrial and engineering applications. Thermosyphon-based systems use a two-phase working fluid circulation to transfer heat from the evaporator to the condenser, creating a continuous thermodynamic cycle. The thermal efficiency of heat exchangers using natural convection and thermosyphon principles depends on factors like working fluid properties, system geometry, and temperature differences between hot and cold regions. Generally, thermosyphon-based equipment is more thermally efficient than natural convection systems. Plate-type heat exchangers are compact and capable of significant thermal exchanges within a small volume using a working fluid. Commercial plate-type exchangers, known as radiators, use electrical resistances to provide energy, inducing internal movements due to density differences. In this study, two radiator-type heat exchangers were employed: one as a reference using oil as the working fluid and the other with modifications to allow testing with distilled water. The prototype used 40% of its total volume as distilled water to evaluate temperature compared to the commercial unit. Data were collected to determine the time required for both plate-type heat exchangers to reach steady-state conditions, and the values converged. This approach effectively enhances performance and reduces energy consumption in such devices. The surface temperature between the hot and cold regions in the adapted heat exchanger was closer due to the characteristic of internal two-phase flow.*

Keywords: *heat pipe, two-phase cycle, radiators, experimental.*

1. INTRODUCTION

Thermal comfort is the mental state that reflects an individual's satisfaction with their environment. It is related to the feeling of well-being in response to thermal conditions, which can be either pleasant or unpleasant, depending on the balance between the heat generated by the body and the heat dissipated by the surroundings. When, there is an imbalance in this heat transfer, either due to excessive heat or cold, thermal comfort is affected, leading to feelings of discomfort. In this context, thermal comfort is essential for people's well-being and productivity in their surroundings (Lamberts, 2016).

The main climatic variables that affect thermal comfort are temperature, humidity, air velocity, and thermal radiation. These factors significantly impact the sensations of comfort or discomfort experienced by individuals in their surroundings. Human demands for thermal comfort are closely related to the body's functioning and the performance of daily activities. When thermal conditions are suitable, meaning there is no thermal fatigue or stress, people enjoy a better quality of life and health, allowing their bodies to function more efficiently. Therefore, understanding and creating environments that consider these climatic factors is crucial to providing maximum thermal comfort to individuals, ensuring well-being, productivity, and health in everyday activities (Frota and Schiffer, 2001).

Therefore, it is essential to use devices that transfer heat to the environment to achieve thermal comfort. For cold climates, among them are resistance heaters, halogen heaters, fan heaters, and other similar options, for cold climates. The market offers various models and formats for these devices, providing numerous choices to meet individual needs and preferences.

Heat exchangers are equipment developed over the years and are present in various devices, such as heaters, refrigerators, and air conditioning systems. They operate based on the principles of thermodynamics and aim to exchange heat between the working fluid and the surrounding environment or another fluid. Their primary purpose is to facilitate heat transfer between the working fluid and a specific domain or another fluid. This process enables thermal regulation and control, contributing to these systems' efficient and proper functioning (Bergman and Lavine, 2020).

Thermosyphons, or gravity-assisted heat pipes, are heat transfer devices that operate based on a highly efficient thermal transfer process. These systems are designed to exchange heat from the hot surface to the cold surface, using the evaporation and condensation of a working fluid that circulates internally through their walls. The working fluid, typically a volatile liquid, carries the heat absorbed from the hot surface through evaporation, transforming into vapor. The upward-flowing vapor moves towards the cold surface, where condensation occurs, releasing heat and transforming it into liquid. This cooled liquid returns to the hot surface due to gravity's action, initiating the thermal transfer cycle again, as shown in Figure 1. This approach enables thermosyphons to achieve a highly efficient and self-sustained heat transfer without requiring pumps or moving parts. These characteristics make thermosyphons a better option in various applications, such as cooling systems for electronics, solar panels, and other situations requiring passive and reliable heat transfer optimization (Naresh, 2017; Mantelli, 2021).

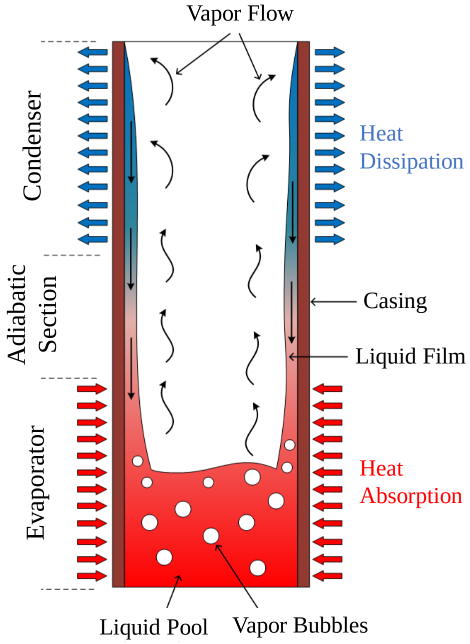

Figure 1. Working principle of a thermosyphon (Machado et al., 2023).

In this context, the present study aims to experimentally evaluate the operation of a flat-plate heat exchanger, commercially known as a radiator heat exchanger, operating under a two-phase flow, where one uses its commercial setup while the other uses the thermosyphon's principle, oil, and distilled water were used as working fluid respectively. Both devices use pressures below atmospheric.

2. METHODOLOGY

This section overviews the thermosyphons' characteristics and the manufacturing process. Additionally, it outlines the experimental apparatus and the experimental procedure employed in the study.

2.1 Characteristics of the heat exchanger

For the tests, commercial heat exchangers were used, one without modifications for control tests and another one that adapted to enable temperature and internal pressure measurements, as well as the possibilities of filling with different working fluids and various filling ratios, which represents the volumetric fraction of fluid inserted into the heat exchanger relative to its total volume.

These devices are manufactured from carbon steel and have a total volume of 2.85L. They consist of seven regions with channel narrowing, referred to as finned regions, and two areas with higher fluid concentration. The cleaning process, assembly, tightness testing, evacuation, filling with the working fluid, experimental tests, and thermal analysis were conducted based on the information provided in Antonini Alves et al. (2018).

2.2 Experimental apparatus and procedure

For the experimental evaluation, it was necessary to instrument the heat exchangers. Figure 2 shows the experimental apparatus used during the evaluation, containing thermocouples, a pressure transducer, and a data acquisition system. In the commercial heat exchanger, 10 type K thermocouples were installed on the external wall of the device. In the heat exchanger assisted by the thermosyphon's principle, 10 type K thermocouples were installed on the outer wall of the device, 10 type K probe thermocouples, and one pressure transducer. All the measurement instruments were connected to a DAQ970A Keysight® Data Acquisition System, which includes two multiplexers containing 20 channels.

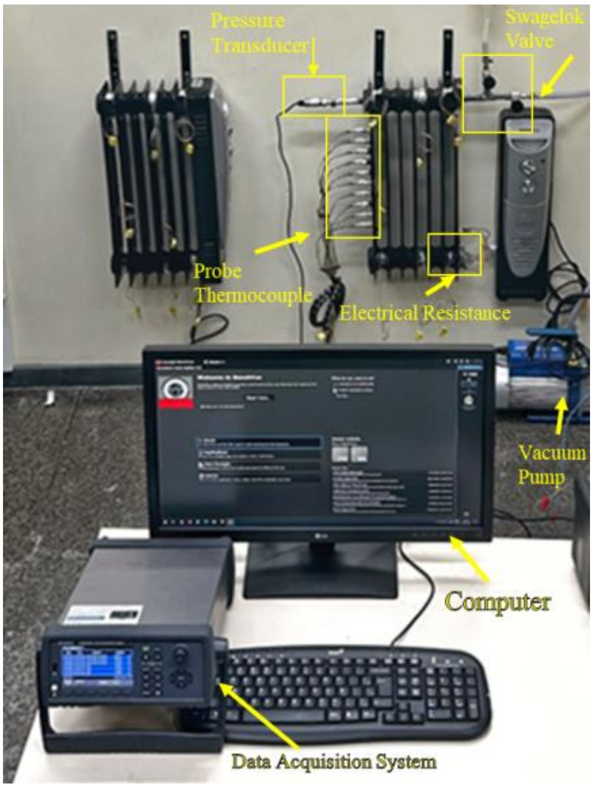

Figure 2. Experimental Apparatus

To control the incoming and outgoing fluid volume, needle valves of the Swagelok® brand were installed. For the evacuation procedure, a vacuum pump from EOS® with a capacity of 12CMF was connected to one of the outlets. A leak test was conducted to ensure proper assembly and complete sealing of all connections. This test involved pressurizing the device while covering all connections with soap suds. An air compressor substituted the vacuum pump, pumping air into the device. If any bubbles were observed in the connections, it indicated the need to redo the assembly process.

After the apparatus was approved at the leak test, a vacuum procedure started, using Dow Corning® vacuum grease on the connections and turning on the vacuum pump for eight hours. Having completed this stage, filling with working fluid begins, closing all evacuation connections and preparing the graduated burette, filling it with working fluid at different fillings ratios.

For the data acquisition procedure, the informations (temperature and pressure) were done by the data acquisition system and saved in the Keysight® BenchVue 2020 software with a 10-second interval between each temperature record. Thermal analysis was based on two points: temperature distribution over time and thermal images using Flir® T400 Series High-end infrared thermal imager to compare the distribution on the device.

2.3 Experimental uncertainties

For the evaluation of experimental uncertainties, the measurement instruments used in this experiment are listed in Table 1.

Table 1. Experimental uncertainties

Parameter	Measuring Instrument	Uncertainty	Unit
Diameter	Caliper	± 0.025	mm
Length	Graduated Scale	± 0.5	mm
Temperature	Type K Thermocouple	± 0.25	°C
Volume	Graduated Burette	± 0.05	ml

In the case of uncertainty analysis, the results of experimental measurements must lead to a measurement uncertainty. This analysis is necessary to estimate the degree of doubt associated with the measurement result. To perform the uncertainty analysis, the uncertainty method described by Holman (2011) was used. By combining uncertainties of related magnitudes, the Engineering Equation Solver® (EES®) software was used to propagate the uncertainties. The uncertainty ΔR of a result $R = f(x_1, x_2, ..., x_n)$ with measurements in $x_1, x_2, ..., x_n$ is expressed by Eq. (1) (Kline and McClintock, 1953).

$$\Delta R = \sqrt{\left(\frac{\partial R}{\partial x_1}\partial x_1\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}\partial x_n\right)^2} \; . \qquad (1)$$

3. RESULTS AND DISCUSSION

The temperatures recorded on the heat exchanger's surface and the thermal camera images be utilized for comparative analysis, aligning with the defined objectives within the scope of this study.

Figure 3 shows the temperature distribution by the time on the commercial heat exchanger, were applied loads between 0 to 1,600W and natural convection is responsible for the cooling of the device. It is possible to visualize that given the increase of the thermal load applied, there is an increase in the average temperature of the regions. It is also noted that the upper region has a higher average temperature when compared to the lower region, which can be explained by the fact that the internal fluid moves through the convection currents formed by the difference in density as a function of temperature. When the highest thermal load is applied, the device's safety devices are activated for the user's safety, considering that the device is designed for domestic use and high temperatures can generate risks.

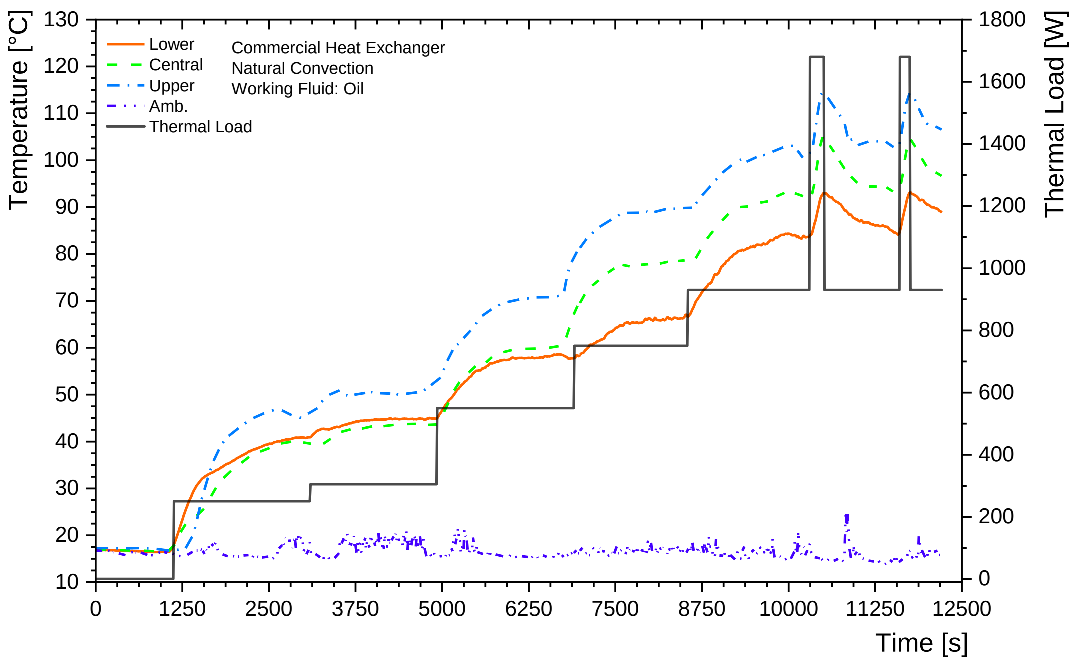

Figure 3. Temperature distribution and thermal load applied by the time on the commercial heat exchanger.

Thermal images of the commercial heat exchanger are showed at Figure 4. The heating initiates in the lower region, primarily concentrated in the rightmost section, where the electrical resistance is situated. However, the temperature distribution of the regions above it undergoes rapid modification due to the increasing temperature they experience.

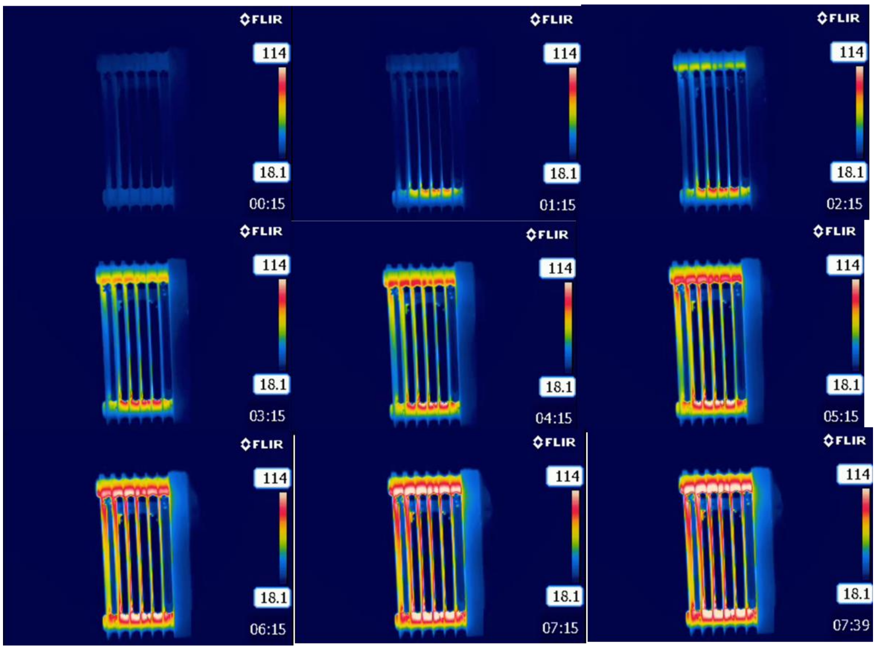

Figure 4. Thermal images by the time on the commercial heat exchanger.

Figure 5 shows the temperature distribution by the time on the adapted heat exchanger, were applied loads between 0 to 1,600W and natural convection is responsible for the cooling of the device, the same as the commercial ones; it is possible to visualize that given the increase of the thermal load applied; there is an increase in the average temperature of the regions. Upon examining the graph's behavior in different regions, it becomes apparent that the temperature gradient was slight compared to the commercial heat exchanger; this characteristic is closely linked to the thermal exchange mechanism, which encompasses the two-phase flow. According to the existing literature, this mechanism is more efficient than thermal exchanges accomplished solely through conduction or convection. Similarly, as witnessed in the commercial exchanger, the protection systems were triggered when the wall temperatures reached 100ºC, in accordance with the specified purpose outlined in the project.

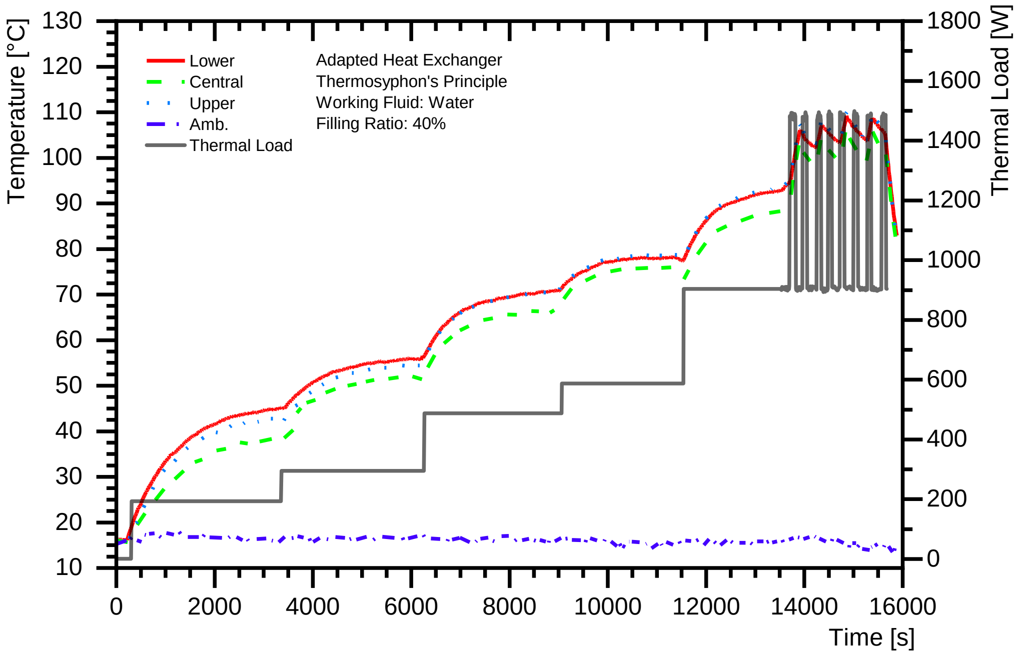

Figure 5. Temperature distribution and thermal load applied by the time on the adapted heat exchanger.

When comparing the images depicted in Figure 6, which showcase the heat exchanger operating based on the thermosyphon's principle, a consistent homogeneity over time becomes evident. In contrast, the images displayed in Figure 4 exhibit a more pronounced gradient.

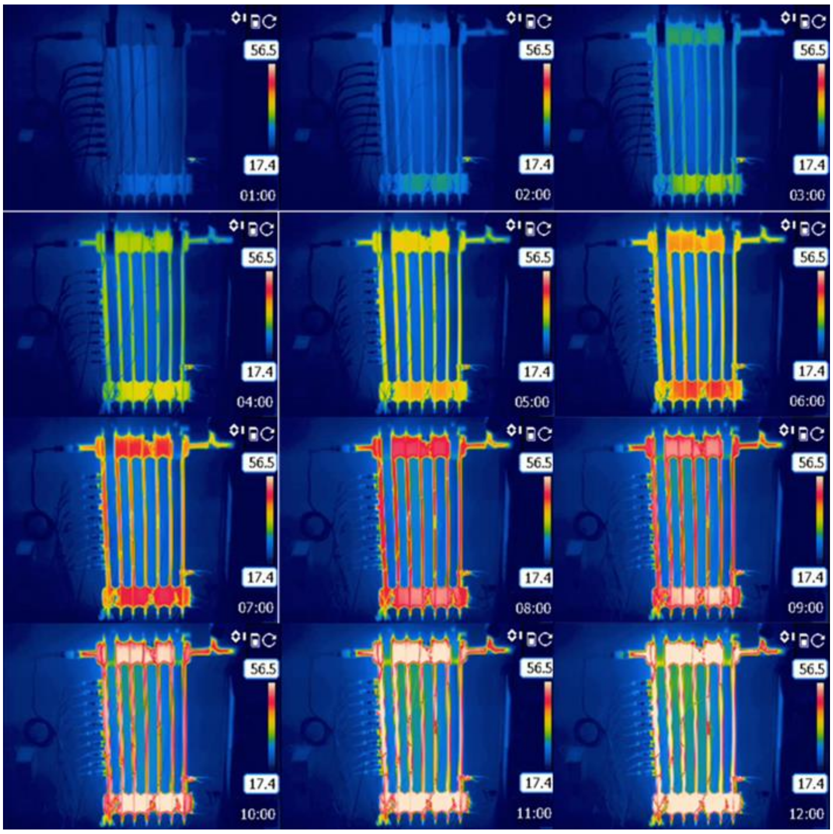

Figure 6. Thermal images by the time on the heat exchanger using the thermosyphon's principle.

Figure 7 shows the behavior of internal pressure as a function of the applied thermal load. As with temperature, when the thermal load applied to the heat exchanger increases, the internal pressure increases until the steady state starts and the pressures are equalized. As a characteristic of the device's sensitivity to the applied thermal load, in the last stage of the test, when maximum power is applied and the device has its safety device activated, a power switching process begins, which aims to maintain the highest possible surface temperature, within limits, and consequently, there is a fluctuation in its internal pressure accompanying this phenomenon.

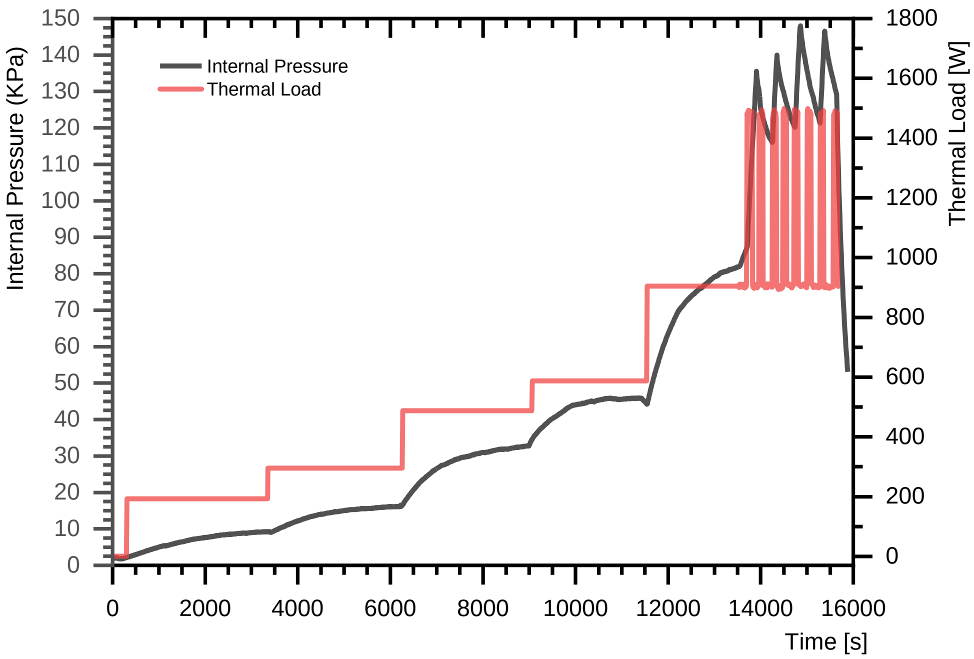

Figure 7. Thermal imagens by the time on the heat exchanger using the thermosyphon's principle.

4. CONCLUSION

This work presents an experimental evaluation that compares two different plat-type heat exchangers. The first uses oil as the working fluid and employs natural convection as the heat transfer mechanism, while the second heat exchanger uses distilled water as the working fluid and operates based on the thermosyphon's principle, facilitating heat transfer through a two-phase flow. Energy was supplied to the system through the Joule Effect, where electrical energy is converted into thermal energy through an immersion resistance. Both heat exchangers demonstrated satisfactory performance under various applied thermal loads, with their safety systems activated when wall surface temperatures exceed 100°C. The adapted plat-type heat exchanger presented a slight thermal gradient, evidenced by the temperature distribution during the tests and shown in the thermal images. Due to its two-phase flow operation, the thermosyphon's principle exhibited its efficient heat transfer capabilities, exchanging substantial amounts of heat.

5. ACKNOWLEDGEMENTS

We thank the Federal University of Technology - Parana (UTFPR), PPGEM, CNPq, and CAPES.

6. REFERENCES

Antonini Alves, T., Krambeck, L., and Santos, P.H.D., 2018. Heat pipe and thermosyphon for thermal management of thermoelectric cooling. In Aranguren, P. (Org.). *Bringing thermoelectricity into reality*. InTech, London.

Bergman, T., and Lavine, A., 2020. *Fundamentals of heat and mass transfer*. Wiley, New Jersey.

Frota, A.B., and Schiffer, S.R., 2001. *Manual de conforto térmico*. Studio Nobel, São Paulo.

Holman, J., 2011. *Experimental methods for engineers.* McGraw-Hill, New York.

Kline, S.J., McClintock, F.A., 1953, Analysis of uncertainty in single-sample experiments, Mechanical Engineering, Vol. 75, pp. 3-8.

Lamberts, R., 2016. *Desempenho térmico em edificações*. Universidade Federal de Santa Catarina, Florianópolis.

Machado, P.L.O., Pereira, T.S., Trindade, M.G., Biglia, F.M., Santos, P.H.D., Tadano, Y.S., Siqueira, H., Antonini Alves, T., 2023, Estimating thermal performance of thermosyphons by artificial neural networks, Alexandria Engineering Journal, Vol. 79, pp. 93-104.

Mantelli, M.B.H., 2021. *Thermosyphons and heat pipes: theory and applications*. Springer Nature, Cham.

Naresh, Y., Balaji, C., 2018, Thermal performance of an internally finned two phase closed thermosyphon with refrigerant R134a: A combined experimental and numerical study, International Journal of Thermal Sciences, Vol. 126., pp. 281-293.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.