EXPERIMENTAL EVALUATION OF THERMAL PERFORMANCE OF A HEAT EXCHANGER USING THERMOSYPHONS

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ABSTRACT

Heat exchangers are devices that aim to improve heat exchange between two fluids at different temperatures, without them mixing. The characteristics that differentiate the types of exchangers are their geometric and constructive shapes, exemplified by the shell and tubes, serpentine, finned, plate, and double tube types, among others. For the present paper, a heat exchanger tube is used, which is connected by thermosyphons to carry out the thermal exchange between the fluids without mixing them. In order to increase the thermal efficiency of the heat exchanger, it is necessary more efficient thermal exchange devices. For this purpose, in this case, we use thermosyphons. The goal of this experimental study is to evaluate the thermal efficiency of the heat exchanger using thermosyphons. In this study, the thermosyphons were manufactured in copper with outer diameter of 9.45mm, an inner diameter of 7.75mm, and a total length of 180mm. The condenser, evaporator, and adiabatic sections all have the same size of 60mm. Three thermosyphons connected the two fluids of the heat exchanger, each one filled with distilled water with a filling ratio of 40% of the evaporator volume and experimentally tested with an angle of 67.5º relative to the horizontal with the surfaces at fixed temperatures (Dirichlet conditions) and the cooling being carried out by convection forced water. The thermal analysis was based on the temperature distribution along the length, the operating temperature, and the thermal resistance. Given the results observed for the thermal resistance, it was possible to find the thermal efficiency of the heat exchanger.

NOMENCLATURE

A	area, m^2
C	heat capacity rate heat, W/K
c_p	specific heat at constant pressure, J/(kg.K)
C_r	heat capacity ratio
$\dot{m}$	mass flow rate, kg/s
NTU	number of transfer units
q	heat transfer rate, W
T	temperature, K or ºC
U	overall heat transfer coefficient, $W/m^2 \cdot K$

Greek symbols

ε	effectiveness

Subscripts

c	cold
h	hot
in	input
lm	log mean condition
max	maximum
min	minimum
out	output

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1. INTRODUCTION

The search for renewable and efficient energy use in the industry has been increasing as the demand for this commodity only rises, and the amount of energy waste in a heat format still sits around 60%. Thus, the energy recovery field brings much interest once the waste is not only of economic value but also reduces the environmental impact of such loss (Cullen and Allwood, 2010). Heat exchangers are devices that use two fluids flowing in different temperatures separate from each other and facilitate heat exchange. Among the several types of heat exchangers, the most common are shell and tube, serpentine, finned, plate, and thermosyphon heat exchanger. The use of this device in the industry can be applied in several areas, especially those needing precise temperature control. The thermal performance of a heat exchanger affects the whole system subjected to the exchanges provided. Enhancing the thermal performance and the heat exchangers' design directly implicates the reuse of the energy loss in other processes (Bergman and Lavine, 2019).

Thermosyphons use the gravity forces and pressure gradient acting in the working fluid to generate heat exchange. The main characteristics of this device can be seen in Figure 1, where the three sections are highlighted: evaporator, adiabatic section and condenser. The working principle of a thermosyphon follows the heat delivered to the evaporator section, where the working fluid is subjected to a liquid-vapor phase change. The pressure gradient will guide the generated vapor through the adiabatic section reaching the condenser, where the vapor will then condense, and heat will be removed from the system. The vapor-liquid phase change on the condenser will return the liquid to the evaporator through the gravity forces (Reay et al., 2014).

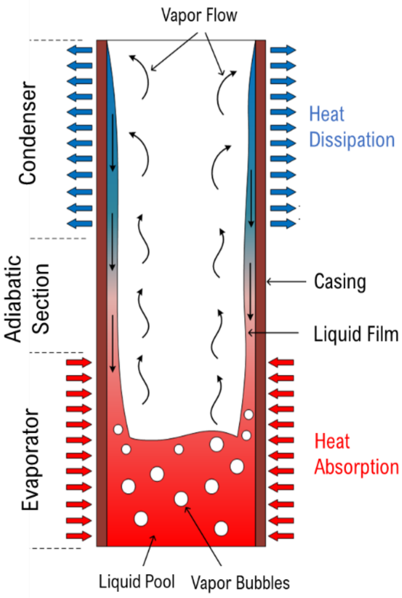


Figure 1. Characteristics and working principle of thermosyphons.

The construction of a thermosyphon comprises the fabrication of a tube closed in its extremity containing the working fluid. This tube or casing must bear the internal and external pressure differences and be compatible with the ambient and the working fluid. To avoid the generation of non-condensable gases, the tube should not react chemically with the working fluid. Usually, the casing material is a metal, and its selection depends on the mechanical forces of the pressurized vapor and operation temperature. The working fluid selection happens in a way that it can perform the expected thermodynamic cycle given the operation temperature. Therefore, the fluid must operate within its melting and boiling points.

The filling ratio of the thermosyphon is an important factor that affects its performance. The Geyser boiling phenomenon is the occurrence of large bubbles formed and bursting in the evaporator. Lower filling ratios present a shorter startup time and lower startup temperature, which also usually avoids the Geyser boiling regime. Since gravity forces are responsible for returning the fluid to the evaporator section, the vertical component of gravity is also a factor observed. In order to guarantee the best operation of the device, its inclination with the horizontal can be adjusted to meet the best operation cycle (Mantelli, 2020; Cisterna et al., 2020).

Thermosyphon heat exchangers are usually an alternative to the traditional heat exchangers mainly due to their very flexible geometry, with many different configurations and easily adjustable to several applications. Another advantage is maintenance since the hot and cold streams are external to the tubes. In addition, there is no system contamination if one tube is compromised. In the case of a heat exchanger using several thermosyphons, the loss of one tube will be compensated by others once thermosyphons are very adjustable to the variation of power input. The construction of this device is not complicated, and the components are easy to acquire. Furthermore, most applications use water as the working fluid (Mantelli, 2020).

Therefore, considering what was present up to this point, this study's goal is to evaluate the thermal performance of a thermosyphon heat exchanger. To achieve that, a thermosyphon heat exchanger was constructed using three thermosyphons containing a 40% filling ratio and tested with an angle of 67.5º relative to the horizontal, according to the study developed by Chagas Vaz (2022).

2. METHODOLOGY

This section presents the equipment and procedures used to accomplish this study goal. For the thermosyphon, the steps of preparation, cleaning, assembling, leakage test, vacuum pumping, filling with the fluid, and crimping and brazing process followed the instructions according to Antonini Alves et al. (2018).

2.1. Thermosyphon Heat Exchanger Characteristics

The thermosyphon tubes were constructed with copper ASTM B-75 with an outer diameter of 9.45mm, an inner diameter of 7.75mm, and a length of 180mm, of which 60mm is for the evaporator, 60mm for the adiabatic section, and 60mm for the condenser. The working fluid was distilled water, with a filling ratio of 40% of the evaporator volume. The three thermosyphons were connected in two PVC pipes of 250mm in length each, with a diameter of 60mm. The placement of thermosyphons was 40mm from each other. In order to acquire the temperature of the stream at the entrance and exit of the heat exchanger, four thermocouples ($T_{h,in}$, $T_{h,out}$, $T_{c,in}$, $T_{c,out}$) type K Omega Engineering™ were placed as shown in the Figure 2.

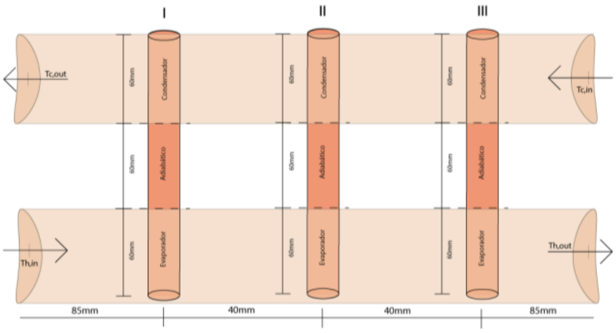


Figure 2. Thermosyphon Heat Exchange arrangement.

2.2 Experimental procedure and apparatus

Two thermostatically-controlled water baths (Figure 3) were used to provide the hot and cold streams, the SL-130 Solab™ for the cold stream, and the LT 204 Limatec™ for the hot stream. Two water rotameters, Omega Engineering™ FL-2050 and FL-2051 of 1.6L and 3L, respectively, were connected in each one of the water baths to control the fluid flow entering the heat exchanger. The connection between the equipment used rubber hoses to attach the male straight hose connectors at each end of the heat exchanger. In order to collect the temperature data, it was used an acquisition data system Agilent™ DAQ970A with a 20 channels multiplexer and a Dell™ computer. The laboratory temperature was set at 20±2ºC, using an air-conditioning unit Carrier™.

To perform the experimental tests, the hoses were connected to the male straight hose connectors so that the hot and cold streams were counter-current. Both thermostatically-controlled water baths were filled with distilled water. The cold one was set to a temperature of 14.5ºC, while the hot one started at 40ºC, then raised to 50ºC and finally to 55ºC. The rotameters were adjusted so that the flow was 0.2L/min for the cold stream while the hot stream was 1.0L/min. For each temperature, the system was subjected to 600s in a steady state. The collected data was evaluated and saved using the software Agilent™ BenchLink Data Logger 3, where the interval for the temperature acquisition was 10s.

Figure 3. Experimental apparatus.

The thermal performance of the experiment was evaluated by using the temperature distribution at the entrance and exit of the heat exchanger. The temperature of the points $T_{h,in}$, $T_{h,out}$, $T_{c,in}$, and $T_{c,out}$ were used to obtain the ΔT_h and ΔT_c. Furthermore, the equation below can determine the thermal effects using the NTU-ε Method.

$$\varepsilon=\frac{\dot{m}_h c_{p,h}\left(T_{h,in}-T_{h,out}\right)}{C_{min}\left(T_{h,in}-T_{c,in}\right)}, \quad (1)$$

where, $T_{h,in}$ and $T_{h,out}$ are the input and output temperatures of the hot stream and $T_{c,in}$, and $T_{c,out}$ are the temperatures of the cold stream. C_{min} and C_{max} are the conductance parameter that represents the maximum and minimum values between C_h and C_c, where $C = \dot{m}\, c_p$. Also, $C_r = C_{min}/C_{max}$ and the Number of Transfer Units (NTU) can be determined from:

$$NTU=\frac{UA}{C_{min}}=\frac{1}{1-C_r}\ln\left(\frac{1-\varepsilon C_r}{1-\varepsilon}\right) \quad (2)$$

The Equation (2) can be arranged in a way to obtain the value of UA, and then the heat transfer can be found using the equation below.

$$q=UA\Delta T_{lm} \quad (3)$$

where the ΔT_{lm} can be determined by,

$$\Delta T_{lm}=\frac{\Delta T_h-\Delta T_c}{\ln\left(\Delta T_h/\Delta T_c\right)} \quad (4)$$

As previously mentioned, the contour conditions applied were of the first type, that is, constant entry temperature conditions, in order to thermally evaluate the performance of the heat exchanger from the flow output temperature.

3. RESULTS AND DISCUSSION

The boundary conditions being expressed as a function of the inlet temperature of the hot flow and as a function of the inlet temperature of the cold flow are presented in Table 1, based on the premise that there are no mass losses during the test and that the specific heat of the fluid is given at constant temperature.

Table 1. Proposed experimental tests.

Test	Hot flow inlet [ºC]	Cold flow inlet [ºC]
#1	40	14
#2	50	14
#3	55	14

Figure 4 shows the heat exchanger operating permanently and in counter-current flow given a hot flow inlet temperature of 40ºC. It is possible to observe that the hot flow lost just over 1°C while the cold flow gained 4°C. This is due to the heat exchanger's operating conditions because there were exchanges with the environment, and it can be concluded that the heat exchanger had an efficiency of 16.3% in these operating conditions.

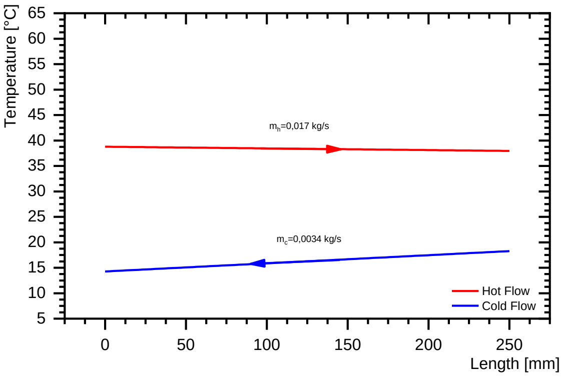
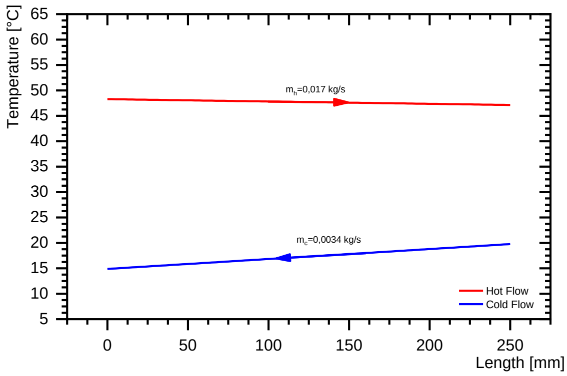


Figure 4. Heat exchanger operating at Test #1.

Figure 5 shows the heat exchanger operating permanently and counter-current flow given a hot flow inlet temperature of 50ºC (Test #2). It is now observed that the hot flow suffered a loss of 1.2°C while the cold flow gained about 4.9°C. This is due to the operation of thermosyphons. The increase in temperature from Test #1 triggered the device's initialization, and the temperature gradient followed the working principle of Figure 2. Thus, it can be concluded that the heat exchanger had an efficiency of 17.4% in these operating conditions.

Finally, in Figure 6, the heat exchanger operates permanently and counter-current flow given a hot flow inlet temperature of 55ºC(Test #3). The hot flow suffered a loss of 1.7°C while the cold flow gained about 6.9°C, with an efficiency of approximately 20.6%. This result is due to the exchanger losing heat in the connections where the devices are installed.

Figure 5. Heat exchanger operating at Test #2.



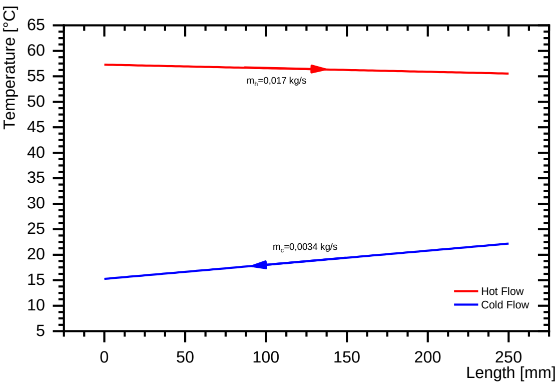


Figure 6. Heat exchanger operating at Test #3.

Furthermore, taking into consideration the proposed experimental tests in Table 3, plus assuming there are no mass losses during the test and that the specific heat of the fluid is given at constant temperature, we can use the equations presented in the methodology section to obtain the parameters displayed on Table 2 below.

Table 2. Heat exchanger parameters.

Test	ε	NTU	q [W]
#1	16.3%	0.181	5.0
#2	17.4%	0.195	7.1
#3	20.6%	0.236	12.3

4. CONCLUSIONS

This study was done following an investigation of the thermal performance of a thermosyphon heat exchanger, composed of three thermosyphons fabricated in copper, using distilled water with a 40% filling ratio and tested with an angle of 67.5º. The heat exchanger was induced to a counter-current stream system, using two water baths connected to rotameters that allowed the flow to be adjusted, using a flow of 0.2L/min for the cold stream and a flow of 1.0L/min for the hot stream. The results show that given an increase in temperature on the hot flow stream, the heat exchange increases as the stream flow are kept constant, and the thermosyphon cycle is activated.

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