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CONSTRUCTION OF A DIDACTICAL WORKBENCH FOR A PERFORMANCE ANALYSIS OF A HEAT EXCHANGER CONTRACORRENT HUB

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Abstract. *This project consists of the construction of a didactic workbench, which is able to provide practical data for the study of the thermal performance of a countercurrent hull heat exchanger. The design was divided into three stages: hydraulic part, support and control. The first one consists of two reservoirs, the reservoir 1 being used to circulate the heated water from circuit 1, which runs through the entire hull of the exchanger and returns to its reservoir, while circuit 2 promotes water circulation that runs through all passes from the exchanger tubes returning to the reservoir 2. The support structure has been dimensioned to accommodate the system as a whole. The third and last stage was the assembly of the control system, which is composed of an arduino board, globe valves and flow sensors (Hall type sensor). At the end of the construction, the following tests were performed: the globe valves of the two circuits were tested in the open state; with the circuit 1 fully open and the circuit 2 50% open and also with the circuit 1 50% open and the circuit 2 fully open. Then, with the aid of thermometers, the inlet and outlet temperatures of the fluid were measured for the operation configurations described above. Two methods of analysis of the data obtained in the heat exchangers were used: LOG mean of the temperature differences and the effectiveness-NUT method. After performing a calculation routine in MS-Excel software, the required heat rates, effectiveness, NUT and overall heat transfer coefficient (U) were determined. The values found were within a plausible range with the references used, which gives reliability to the data.*

Keywords: *Didatical workbench, Thermal Performance, Hull and tube heat exchanger.*

1. INTRODUCTION

Heat transfer (or heat flow) is the thermal energy in transit due to a difference in temperatures in space (INCROPERA and Dewitt, 2014). Heat exchangers, in turn, are dimensioned equipment and used to promote the exchange of heat between fluids, preventing them from mixing during the process (WHITE, 2011).

Heat exchangers are equipments that have an enormous range of applications in the most varied places, always in conditions where it is necessary to effect thermal exchange between fluids. Examples of applicability are: various industrial sectors, commercial establishments and domestic residences

With the respective scenario in view, it is possible to perceive the fundamental importance of understanding the basic principles involved in the physics of the operation of heat exchangers, since it is necessary to guarantee that the specific demands made to the exchanger are met, avoiding losses in the system and, consequently, undesirable side effects.

The use of didactic workbenches is a practical and effective way to analyze and validate the theory taught in the classroom. These components are able to simulate systems in real conditions or close to use. Often, test workbenches are integrated into the development of projects of the most varied types.

Observing the need to solve a problem, together with a form that has been obtaining good results, the respective work details the process of construction of a didactic workbench to analyze the performance of a heat exchanger tube hull, which will be of fundamental importance to provide the students of mechanical engineering of the Laboratory of Fluids and Thermal of the Federal University of Pará, Campus of Tucuruí (CAMTUC) a practical tool for the study of the physical phenomena that accompany the operation of this component.

2. MATERIALS AND METHODS

The construction of the workbench was segmented into four stages: revitalization of the exchanger; construction of hydraulic circuits, support and control; workbench construction and validation.

2.1. Revitalization

The casing of the heat exchanger tube hull was obtained from a donation from Eletrobras Eletronorte Brazil's Power Stations Company from a Self Contained to the Faculty of Mechanical Engineering of the Federal University of Pará - CAMTUC.

This structure was subjected to a hygienization process in order to eliminate impurities and possible residues. The cap threads had to be revitalized. After cleaning the housing and machining the fixing threads, the structure was sanded and painted in the emblem green color, as indicated in the standard NBR 6493/1994, which uses the respective color to indicate pipes where water circulates (except in cases of fire). Fig. 1 shows the structure: a) before and b) after the revitalization process.

Figure 1. Heat exchanger housing: a) before and b) after revitalization.

2.2. Workbench Construction

2.2.1. Hydraulic Circuits

For the assembly of the hydraulic system, weldable Polyvinylchloride (PVC) tubes with a diameter of Ø 0,020 m were used. The material in question was chosen due to its low financial cost, easy handling, great availability in the market, lightness and good resistance.

2.2.2. Support Structure

The material chosen was the Medium Density Fiberboard (MDF) because it was resistant and stable. Due to its intrinsic characteristics, this material is widely used in the construction of furniture and structures in general. Because it is a worktop that is likely to come in direct contact with the fluid (water), it was necessary to coat the structure with a type of laminate paper known as malamínico, widely used in the coating of furniture and environments in general, as it offers greater resistance to humidity, temperature, stains and scratches.

The dimensions of the workbench structure are as follows: height - 1,20 m; length - 1.00 m; width - 0.50 m and thickness - 0.0040 m. These measures were adopted in order to allow the operator to be able to use it as a support table to accommodate a microcomputer or notebook, and also to fix the arduino board safely, position the thermometers and make notes.

2.2.3. Control System

The control system is used in the real-time monitoring of one of the circuits during the workbench operation, using the properly programmed Arduino board, which receives the data informed by the Hall sensor, accompanied directly on the platform of the board with the use of a notebook. The flow variation is provided by a globe valve, which allows adjustments according to the desired intensity.

2.2.4. Workbench Mounting

In the process of assembling the workbench, the following tools were used: drill with varied sizes of drills, a cup saw and manual sawing bow.

The design of the workbench was determined to obtain two circuits, being: circuit 1 (hot) and circuit 2 (cold). To this end, it was also necessary to consider the availability of a space that houses the heat exchanger and the two water reservoirs (1 and 2), as well as the structures of the hydraulic circuits and their respective components, which have been dimensioned in order to avoid losses of significant charges. Fig. 2 shows: a) fully constructed and operable workbench; b) arrangement of thermometers, arduino board and notebook.

Figure 2. a) built workbench; b) thermometers, arduino board and notebook.

2.3. Workbench Validation

In order to validate the workbench, volumetric flow tests were performed with 100% open globe valves; with circuit configuration 1 (50% open) and circuit 2 (100% open) and also for the reverse configuration. The obtained data were used to find the equivalent mass flow rates of each circuit analyzed as a function of the input temperature of the circuits. Circuits 1 and 2 are described in more detail in subtopics 2.3.1 and 2.3.2, respectively.

2.3.1. Circuit 1 (Hot)

Circuit 1 has been dimensioned so that heated fluid exits reservoir 1 through a 500 Gph flow pump with about 0.52x10-4 m^3/s, passes through the flow control valve, and then passes through the sensor Hall, entering the heat exchanger through the copper tube (Ø 0,018 m). In this way, the hull volume is completely filled. After this, the fluid exits the top of the hull and returns to the reservoir 1. When the pump is turned off, it is mandatory to close the globe valve to prevent the reservoir 1 from overflowing, which could compromise the integrity of the electric heater. Fig. 3 shows the circuit 1, being: 1) reservoir; 2) pump; 3) globe valve; 4) Hall sensor: 5) heat exchanger; 6) Electric heater and 7) Arduino board.

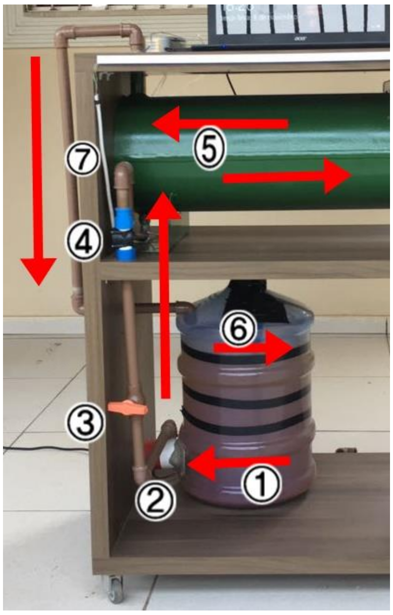

Figure 3. Circuit 1 (Hot).

2.3.2. Circuit 2 (Cold)

Similar to the circuit 1, the ambient temperature fluid exits the reservoir 2, passes through the globe valve, passes through the Hall sensor, enters the exchanger through the lower tube of the cap, runs through the multipasses (six passes), raises a pass after traveling the length of the tubes and leaves the exchanger through the top tube of the cap, returning to the reservoir 2. Two copper tubes have to be fitted to the inlet and outlet of the circuit 2 due to good thermal conductivity of the material, bringing the incoming and output. Fig. 4 shows the circuit 2, being: 1) reservoir; 2) pump; 3) globe valve; 4) Hall sensor; 5) heat exchanger; 6) Copper tubes and 7) Arduino board.

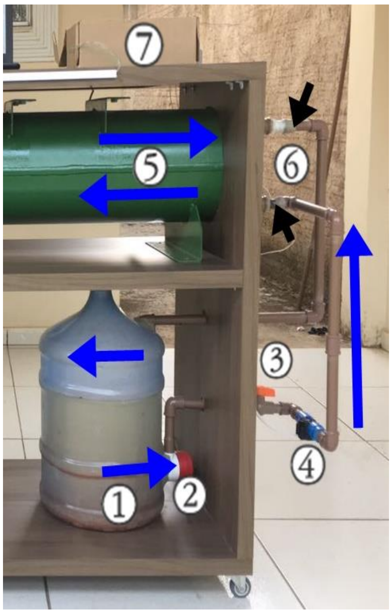

Figure 4. Circuit 2 (Cold).

2.4. Data Obtained on Workbench

Table 1 shows the representative values of U for combinations of fluids (INCROPERA and DEWITT, 2014). Table 2, on the other hand, shows the data taken from the workbench.

Table 1. Representative Values of U (Incropera e Dewitt, 2014).

Fluid Combination	$U[W/m^2.K]$
Water - Water	850 – 1700
Water - Oil	110 – 350
Steam condenser (water in the tubes)	1000 – 6000
Ammonia condenser (water in the tubes)	800 – 1400
Alcohol condenser (water in the tubes)	250 – 700
Changing tube heat exchanger, cross flow air	25 – 50

Table 2. Workbench Data.

Data obtained on the Workbench			
Volumetric Flow (100%)		**Hub Length (L)**	**Inside Diameter of Hub (Di)**
Circuit 1 (L/min)	Circuit 2 (L/min)	(m)	(∅ - m)
5,80	6,50	0,99	0,21
Volumetric Flow (100%)		**Tubes/Pass length**	**Inside Diameter of Tube (Di)**
Circuit 1 (L/min)	Circuit 2 (L/min)	(m)	(∅ - m)
2,90	3,25	1,00 m	0,02

The difference in flow is due to the fact that the circuit 1 pump has no base for the filter, which reduces the flow rate.

Using the data taken from the circuits, the heat exchanger analysis calculations were started. In order to analyze the obtained data, some conditions must be considered in the execution of the calculations:

- The heat exchanger is thermally insulated from the vicinity, so there is only heat exchange between the fluids q and f.
- Axial conduction along the tubes is negligible.
- Changes in kinetic and potential energy are negligible.
- The specific heat of the respective fluids are constant.
- The deposition factors and the thermal resistance of the pipe wall are negligible.
- The overall coefficient of heat exchange (U) is considered constant.

Given the conditions, the next step was to find the properties of water (e) at the inlet temperatures of the heat exchanger. At the end of each test lasting 20 m, the inlet and outlet temperatures of the exchanger were measured. Using the water density table at 1 atm (WHITE, 2011) and the table of thermophysical properties of saturated water (INCROPERA and DEWITT, 2014) found through direct interpolations. The calculated values for all of the respective settings are shown in Tab. 3.

Table 3. Water properties in tests with fully open configuration.

Water Properties				
○ = Valve 100% Open			**● = Valve 50% Open**	
Workbench Configuration	○		○	
$T_{q,ent}$ **e** $T_{f,ent}$	**Circuit 1**		**Circuit 2**	
°C	$\rho_q = kg/m^3$	$C_{p,q} = J/kg \cdot K$	$\rho_f = kg/m^3$	$C_{p,f} = J/kg \cdot K$
Test 1 (42,1 e 34,9)	991,16	4179,02	994,04	4178,00
Test 2 (43,1 e 36,0)	990,76	4179,22	993,60	4178,00
Test 3 (42,2 e 34,8)	991,12	4179,04	994,08	4178,00
Workbench Configuration	●		○	
Test 1 (50,4 e 41,8)	987,84	4181,36	991,28	4178,96
Test 2 (49,3 e 40,7)	988,28	4180,92	991,72	4178,74
Test 3 (48,1 e 39,6)	988,76	4180,44	992,16	4178,52
Workbench Configuration	○		●	
Test 1 (47,5 e 40,7)	989,00	4180,20	991,72	4178,74
Test 2 (46,6 e 39,3)	989,36	4179,92	992,28	4178,46
Test 3 (47 e 39,8)	989,2	4182,00	992,08	4178,56

Due to the behavior of circuits 1 and 2, the calorific value presented small variation, indicating that the mass flow has a fundamental influence on the process. According to Incropera and Dewitt (2014), if or, the heat exchanger enters a special operating state, with one of the fluid temperature remaining practically constant, while the other is heating or cooling, thus making it impossible to analyze the behavior of the inlet and outlet temperatures of one of the circuits along the exchanger. For this reason, it was decided to work in regimes of at least 50,0% flow for both circuits.

2.5. Determination of Required Heat Rate with MLDT Method

The next step is the analysis of the heat exchanger using the LOG mean of the temperature differences in order to determine the required heat transfer rate in the workbench. The circuit with the lowest heat capacity ($m_q \cdot C_{p,q} = C_q$ or $m_f \cdot C_{p,f} = C_f$), which is defined by a global energy balance in the hot or cold fluid, using Eq. (1) and Eq. (2), respectively, is used as reference.

$$q_q = \dot{m}_q c_{p,q}(T_{q,ent} - T_{q,sai}) \tag{1}$$

$$q_f = \dot{m}_f c_{p,f}(T_{f,sai} - T_{f,ent}) \tag{2}$$

After defining the required heat rate in the process, a new global energy balance should be $q_q = q_f$, to find $T_{f,sai}$ or $T_{q,sai}$ comparing it to the value obtained in the measurement and evaluating the difference between them. Eq. (3) and Eq. (4) are in function of $T_{f,sai}$ or $T_{q,sai}$, respectively.

$$T_{f,sai} = \frac{q_f}{\dot{m}_f c_{p,f}} + T_{f,ent} \tag{3}$$

$$T_{q,sai} = T_{q,ent} - \frac{q_q}{\dot{m}_q c_{p,q}} \tag{4}$$

Then, the average temperature variation log ΔT_{lm} along the exchanger is defined, by means of the relation between the inlet and outlet temperatures, as shown in Eq. (5).

$$\Delta T_{ml} = \frac{\Delta T_2 - \Delta T_1}{ln\left(\Delta T_2 / \Delta T_1\right)} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\Delta T_1 / \Delta T_2\right)} \tag{5}$$

Çengel and Ghajar (2012) present a correction factor for tube hull heat exchangers, with a hull pass and multiples of 2 in the tubes, which is the case of the exchanger analyzed in this work. This correction factor is used to analyze the occurrence of load losses in the pipe passes.

The designations T_1 e T_2 represent the input and output temperatures of circuit 1 respectively, as well as t_1 and t_2 for circuit 2. With the known input and output temperatures, the ratios of each test were calculated, thus determining their respective correction factors, by adjusting it to calculate the value of U.

For the countercurrent flow heat exchanger, $\Delta T_1 = (T_{q,ent} - T_{f,sai})$ and $\Delta T_2 = (T_{q,sai} - T_{f,ent})$. The average temperature variation along the exchanger in the tests should be found for the different configurations, representing the behavior of the mean temperatures entering and exiting the exchanger.

2.6. Determination of U with MLDT Method

With the required heat rate, MLDT and the appropriate dimensions of the exchanger (from the hull or tubes) all terms are used to determine the U, using a form to avoid flow analysis and convective coefficient of the hot and cold side, which would involve Reynolds number, Brandt number and dynamic viscosity of the fluid due to lack of information on the internal configuration of the exchanger. U was defined by modified Eq. (6), now as a function of U and the internal area of the hull.

$$U = \frac{q}{A_i \Delta T_{ml}} \tag{6}$$

2.7. Determination of NUT

The next step is the determination of the NUT (Number of transfer units), defined by Eq. (7) (INCROPERA and DEWITT, 2014).

$$NUT = \frac{UA}{C_{min}} \tag{7}$$

2.8. Effectiveness of Heat Exchanger Hull Tube

Using the effectiveness-NUT method, Incropera and Dewitt (2014) describe that, in order to determine effectiveness, it is first necessary to calculate the maximum possible transfer rate using an energy balance based on the minimum calorific capacity and the input temperatures of the circuit 1 and output from circuit 2, using Eq. (8).

$$\boldsymbol{q_{Máx} = C_{min}\left(T_{q,ent} - T_{f,ent}\right)} \tag{8}$$

Based on the results, the effectiveness (ε) is defined as the ratio between the actual heat transfer rates at the exchanger and the maximum possible heat transfer rate, using Eq. (9).

$$\varepsilon = \frac{q}{q_{Máx}} \tag{9}$$

However, this definition of effectiveness is an approximation, which does not consider the type of construction of the exchanger. For this reason, it is necessary to apply the relation of the NUT to C_r. Using Fig. 5, it is possible to define the effectiveness of the analyzed exchanger by measuring the intersection point between NUT and C_r.

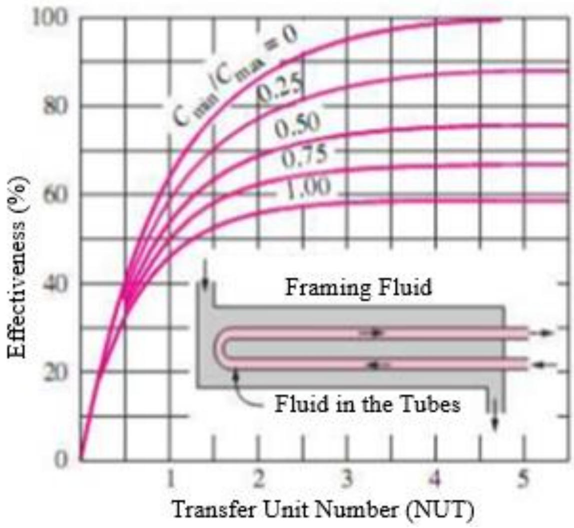

Figure 5. Effectiveness for tube hub exchanger (Adapted from Çengel, 2012).

Using the value of ε, the real heat rate is determined through Eq. (10).

$$q_r = \varepsilon C_{min}(T_{q,ent} - T_{s,ent})\varepsilon = \frac{q}{q_{Máx}} \tag{10}$$

With this data in hand, we can determine the coefficient U for the effectiveness method, through Eq. (11).

$$\boldsymbol{U_{\varepsilon-NUT} = \frac{q_r}{A\Delta T_{lm}}} \tag{11}$$

3. RESULTS AND DISCUSSIONS

To simplify the process, we chose to arrange all the results sequentially, that is, without division by subtopics.

At the end of the whole process of tests and calculations, the values found of e, with the use of the MLDT and the results of NUT, q_r, ε, $U_{\varepsilon-NUT}$ found from the NUT-effectiveness method are expressed in Tab. 4, Tab. 5 and Tab. 6 for the respective configurations used.

Table 4. Thermal performance values for configuration (100%-100%).

Circuit 1 (Hot) - Circuit 2 (Cold)								
Tests	**C. 1**	**C. 2**	**MLTD**		**Effectiveness - NUT**			
			q **(W)**	$U\ (W/m^2 \cdot K)$	qr **(W)**	$U_{\varepsilon-NUT}\,(W/m^2 \cdot K)$	ε	NUT
Test 1	○	○	1.961,71	1.467,76	1.787,16	1.395,42	0,62	2,4
Test 2	○	○	1.841,70	1.253,84	1.705,57	1.161,16	0,60	2,1
Test 3	○	○	1.961,72	1.352,78	1.807,18	1.246,21	0,61	2,2
Average Values	○	○	1921,71	1358,13	1766,64	1267,60	0,61	2,2
○ = Valve 100% open ● = Valve 50% open								

Observing Table 4, it can be seen that the U values remained within the range prescribed by Table 1 of the authors Incropera and Dewitt (2014), in all tests for the 100% -100% configuration. The heat exchanger had an average effectiveness value of 61.0%, while the mean NUT remained around 2.20.

The behavior of the temperatures showed greater variation of values in Circuit 1 (4.8 K loss), while in Circuit 2, there was a gain (3.6 K), showing that the exchanger functioned as a water cooler due to the higher variation between the inlet and outlet temperatures of the hot circuit, when compared to the cold circuit. Fig. 6 shows the average temperature behavior along the exchanger and the LOG mean. The arithmetic mean of the values of the entrance and exit temperatures of the tests was calculated, trying to represent the behavior along the exchanger.

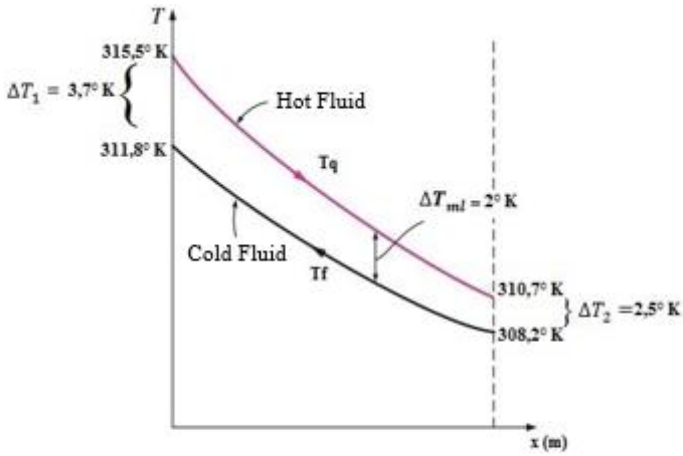

Figure 6. Average temperature test performance by 100%-100%.

Table 5 presents the results obtained for the 50% -100% configuration. For this, the heat exchanger proved to be more effective as a water cooler, with an average effectiveness value of 79.0% and a mean NUT of 3.30, varying with greater intensity in circuit 1 (6.9 K loss) and gain (3.8 K) in circuit 2, respectively. In relation to the fully opened valves, configuration 2 has proved to be more suitable for cooling the water.

Table 5. Thermal performance values for configuration (50%-100%).

Circuit 1 (Hot) - Circuit 2 (Cold)								
Tests	**C. 1**	**C. 2**	**MLTD**		**Effectiveness - NUT**			
			q (W)	$U\ (W/m^2 \cdot K)$	qr (W)	$U_{\varepsilon-NUT}\ (W/m^2 \cdot K)$	ε	NUT
Test 1	●	○	1.402,2	1.065,2	1.395,42	1.059,97	0,81	3,5
Test 2	●	○	1.381,8	1.018,6	1.360,56	1.002,93	0,79	3,4
Test 3	●	○	1.341,6	929,4	1.310,57	907,93	0,77	3,1
Average Values	○	○	1375,2	1004,4	1355,5	990,3	0,79	3,3
○ = **Valve 100% open** ● = **Valve 50% open**								

The temperatures behaved in a similar way to the previous configuration, presenting small variations, as shown in Fig. 7.

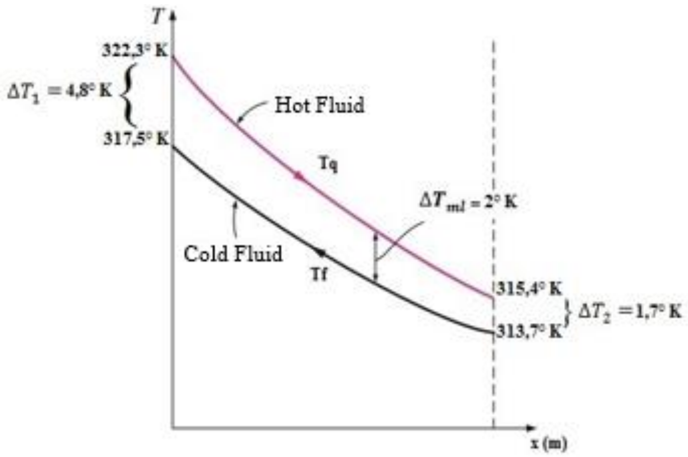

Figure 7. Average temperature test performance by 50%-100%.

Table 6 shows the results for the 100% -50% configuration. Due to the variation in the mass flow, circuit 2 undergoes greater variation between the temperatures (4.4 K gain) and circuit 1 with loss (3.0 K). Because the heat capacity has been reduced by half, the heat exchanger started to act as a water heater, differing from the previously analyzed configurations. The average effectiveness was around 61.0% and the mean NUT was 1.7. This is justified by the fact that the cold fluid flows much slower in this configuration.

Table 6. Thermal performance values for configuration (100%-50%).

Circuit 1 (Hot) - Circuit 2 (Cold)								
Tests	**C. 1**	**C. 2**	**MLTD**		**Effectiveness - NUT**			
			q (W)	$U\ (W/m^2 \cdot K)$	qr (W)	$U_{\varepsilon-NUT}\ (W/m^2 \cdot K)$	ε	NUT
Test 1	○	●	947,7	1232,3	951,3	1237,0	0,62	1,75
Test 2	○	●	1015,4	1414,6	1037,8	1445,8	0,63	2,0
Test 3	○	●	971,5	981,1	959,7	969,3	0,59	1,39
Average Values	○	●	978,2	1209,3	982,9	1217,4	0,61	1,7
○ = **Valve 100% open** ● = **Valve 50% open**								

With the test temperature data, the arithmetic mean was calculated to represent its behavior, as shown in Fig. 8.

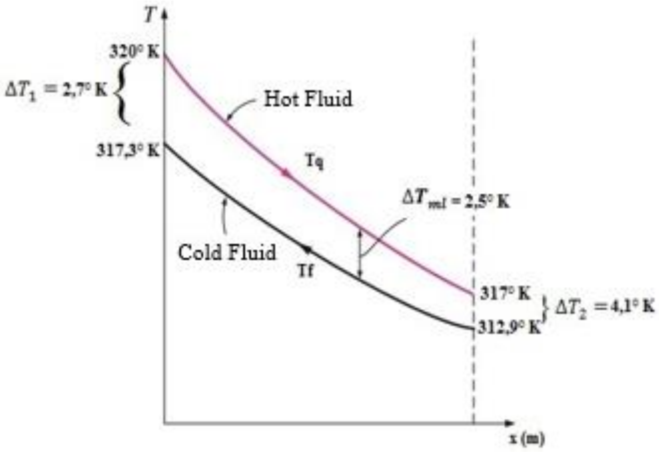

Figure 8. Average temperature test performance by 100%-50%.

The theoretical values of output calculated through the energy balance equations showed differences lower than 1 ºC, both for values higher than theoretical and for those that were lower than expected. Only in the 50% -100% setting, the measured temperature exceeded the theoretical value. Several factors may have influenced this result, however, it is not possible to point out a certain decisive factor. The theoretical and mean output temperatures are contained in Table 7.

Table 7. Theory and measures output temperatures.

Cooler	**C.2 Theory output Temperatures (K)**			**C.2 Measures output Temperatures (K)**		
Tests	**1**	**2**	**3**	**1**	**2**	**3**
100%-100%	312,3	312,2	312,1	311,6	311,3	311,4
50%-100%	317,9	316,8	315,6	318,6	317,6	316,2
Heater	**C.1 Theory output Temperatures (K)**			**C.1 Measures output Temperatures (K)**		
Tests	**1**	**2**	**3**	**1**	**2**	**3**
100%-50%	318,1	317,1	317,5	317,9	316,2	317,1

The results found for both the heat rate and the overall heat transfer coefficient show that the methods differ, but are practically equivalent. A better approximation was obtained with the effectiveness-NUT method, which considers the constructive form of the heat exchanger. However, both methods proved to be effective for analyzing the countercurrent hull heat exchanger. Effectivity values higher than 50.0% were found for the configuration of the 100% open valves, which makes the exchanger viable for the process for which it is intended. Due to the divergence between the results obtained, there was a variation in the overall coefficient, but in both cases analyzed, the coefficients remained within the range indicated by Tab. 1. These results are consistent with the references consulted, besides Incropera and Dewitt (2014) and Çengel and Ghajar (2012), the authors Bistafa (2012), Oliveira and Lopes (2012) and White (2011) make similar observations about analyzes of this type.

4. CONCLUSIONS

After the construction, tests and analysis of the results obtained in the didactic workbench, it was concluded that the heat exchanger proved to be adequate to the objectives proposed in this work, where all components of the system were safely performed, and allowed a performance evaluation thermal efficiency.

The workbench was easy to operate, due to the simplicity in the management of circuit configurations. The temperature variations could be determined and analyzed through graphs. The workbench also has a good didactic aspect, because it is allowing the demonstration, in the laboratory, of processes studied theoretically in the classroom, where phenomena of heat exchange are being viewed in a practical way.

The values of, NUT and in the configurations were found to be 100% -50%; 100% -100% and 50% -100%. The values remained within the ranges found in the references used (ÇENGEL and GHAJAR, 2012 and INCROPERA and DEWITT, 2014) for the transfer of heat using water as test fluid, as well as the behavior of the temperatures along the exchanger in the different circuits, thus validating all the analysis performed on the workbench.

Because it was a didactic workbench, a script was elaborated that describes in detail the procedures to be followed for the execution of experiments. This script will allow anyone with theoretical knowledge in this area to be able to perform tests accurately. This workbench also represents a great gain for the Faculty of Mechanical Engineering of the Federal University of Pará - CAMTUC.

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