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Operation of a Shell and Tubes Heat Exchanger: Process Simulation[1]

Paúl Bolívar Torres-Jara

Universidad Politécnica Salesiana, Sede Cuenca
Calle Vieja 12-30 y Elia Liut, Cuenca, Ecuador

Diego Rafael Lasso-Lazo

Universidad Regional Amazónica IKIAM
Km 7, vía a Alto Tena, Ciudad de Tena, Napo, Ecuador

Efrén Vázquez-Silva

Universidad Politécnica Salesiana, Sede Cuenca
Calle Vieja 12-30 y Elia Liut, Cuenca, Ecuador

Gabriela Abad-Farfán

Universidad Politécnica Salesiana, Sede Cuenca
Calle Vieja 12-30 y Elia Liut, Cuenca, Ecuador

Juan Carlos Galarza-Galarza

INDURAMA
Av. Don Bosco y Av. de Las Américas, Cuenca, Ecuador

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Abstract

The thermo-fluid laboratory at the *El Vecino* campus of the Salesiana Polytechnic University in Cuenca (UPS), Ecuador, has a shell and tube heat exchanger. This experimental equipment is very important from the didactic point of view for subjects such as Fluid Mechanics and Heat Transfer (subjects that are part of the curriculum of the undergraduate program of Mechanical Engineering), as well as to carry out application projects at the institutional level. This paper presents the results of the simulation of heat transfer processes that take place in the heat exchanger, and demonstrates the feasibility of "replacing" the physical equipment by the computer simulation. In addition, are shown the benefits that this possible replacement has for the institution and teaching.

Keywords: Heat exchanger, computer simulation, heat transfer

1 Introduction

Heat exchangers are devices that enable the heat transfer between two fluids at different temperatures without them mixing. These devices are fundamental elements in heating, cooling, air conditioning, energy production and chemical processing systems; therefore, they are used in all types of industries [1, 2].
Approximately 37% of the heat exchangers used for industrial purposes are shell and tubes exchangers [3]. An outer shell, by which one of the fluids flow, as well as several tubes through which the other fluid flows, without them mixing, makes up these exchangers. The equipment works by heat transfer due to conduction and convection. In Chemical Industry, where heat transfer without combustion is required, this type of heat exchanger is essential. In this regard, there are different methods for its design and this leads to a line of research on such devices. For example, in [4] it is possible to find the description and automation of the *Taborek* method, used in order to design a heat exchanger of this type. In addition, the design cost is optimized with the application of the methods Simulated Annealing and Genetic Algorithms. From the point of view of the applications, the research conducted on heat exchangers have been aimed at increasing the efficiency of this devices under different condition of the surrounding environment [5], and to make this possible, computer tools have also been used to develop simulations of state behavior of a heat exchanger.
We also found the report by J. Ardalia and his partners [6]. They validate an *ANSYS* numerical model for the analysis of heat transfer in straight, helical, smooth and torsioned concentric tube exchangers; comparing the obtained results with experimental data published in specialized scientific books. According to their conclusions, the increase of heat transfer is associated to the

geometry of the exchanger. Conclusions of these types of studies have been the basis to improve both the design and the terms of use. They have also helped save financial resources. It is also possible to cite the works of Correa and Marchetti [7], who compared the behavior of three different shell and tube exchangers to find the most effective. They used an artificial network (ANN) to validate theirs experiments, and the maximum deviation they obtained was 2%. On the other hand, Nellis et al. [8] used simulation to validate the experimental results for heat exchangers used in refrigeration, specifically in evaporators and condensers. Comparatively they acted within a margin of 10% and then used simulation to predict the improvement in the efficiency of the exchanger by up to 8.3%.

Kamaris et al. ([9]) applied a computational fluid dynamics (CFD) code to simulate the heat transfer in a plate exchanger. They validated the obtained results in an experimental manner and demonstrated the effectiveness of the CFD code for simulation. While J. Judge and R. Radermacher [10] used simulation data, to develop a heat exchanger model to cool residential heat pumps. The results improved efficiency by 44% and were validated for four different types of refrigerant. Córdova-Tuta and Fuentes Díaz [11] develop a computer tool for the simulation of flow behavior in the tube and fin exchangers when a phase exchange may occur in the refrigerant. In this case, the finite volumes methodology was used for the modeling of the exchanger, and the representation of the tube connections was done by means of the graph theory. With this model, it was possible to predict the behavior of an evaporator's flows when having dry and wet fins; the error was less than 6% with respect to the experimental data. Another application of virtual tools for the study of exchangers is, for example, the use of Hysys. In [12] it is described the validation of the linear multivariable control designs in a heat exchanger under this virtual environment. The study aimed at analyzing the different responses of the *MIMO* system, under regulatory control with different uncouplers and without uncouplers.

The validations of the experimental results have also carried out by applying the numerical methods. Anica Trp [13] conducted comparisons between the numerical and experimental results of the heat transfer in an exchanger as the one being discussed in the present report. Additionally, there is the work of Machuca and Urresta [14], which presents the structure of a software developed for teaching and learning the dynamics and control of a shell and tubes heat exchanger. The program presents, in a numeric and graphic manner, the dynamic behavior in open and closed loop of the process for different parameters of design and variable conditions of operation. For a more complete and detailed information on current issues regarding heat exchangers, the main lines of research and challenges, you can consult the work of Reyes-Rodríguez and Moya-Rodríguez [15].

In our case, we deal with a laboratory equipment, fundamentally used for teaching purposes in the subjects of Fluid Mechanics and Heat Transfer. Therefore, the following question arises: How do we guarantee the laboratory practices in Fluid Mechanics and Heat Transfer when, for some reason, the exchanger is out of service? An answer to the aforementioned question will be given. Hence, the following section describes the materials and methods used to conduct the research. Then, section 3 presents the results of the developed simulation, which describes the processes that take place in the exchanger, and we made a comparison with the data obtained experimentally. Finally, the conclusions are set forth in section 4.

2 Materials and methods

2.1 Experimental issue

The Shell and Tubes heat exchanger analyzed in this work is a teaching model of the thermo-fluids laboratory of the Universidad Politécnica Salesiana. Armfield (Engineering Teaching & Research Equipment) built it. Its characteristics are shown in Table 1.

Table 1: Technical characteristics of the Shell and Tubes Exchanger

Characteristic	**Description**
Brand	**Armfield**
Number of tubes	**7**
Material of the tubes	**Stainless steel**
Lenght of the tubes	144 mm
External diameter of the tubes	6.35 mm
Internal diameter of the tubes	5.15 mm
Material of the Shell	**Acrylic**
Number of deflectors	2
Material of deflectors	**Acrylic**

Figure 1 shows the constructive aspect of the device, it has thermocouples to measure the inlet and outlet temperature of the fluid, and also it has flow meters to measure the hot and cold flows.

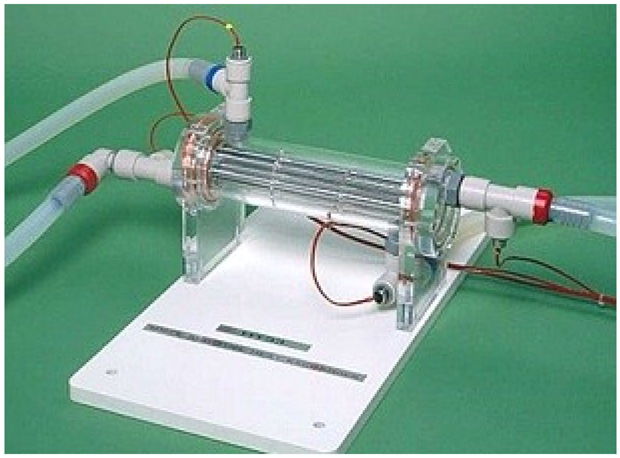


Figure 1: Shell and Tubes Exchanger

2.2 Environmental parameters

The environmental parameters that are normally in the laboratory where practices are developed are shown in Table 2. The value of atmospheric pressure and room temperature were obtained with *JUMO* measurer, which has platinum wire sensors. The measurements were carried out according to the DIN 60751 norm.

Table 2: Environmental parameters

Variable	**Value**
Atmospheric pressure	$75.19 kPa$
Room temperature	$18.05\ ^{0}C$

2.3 Flow and temperature

The flow and temperature variables were established for two types of flow: hot water and cold water; following the direction of the flow, as shown in Figure 2. The initial values for these variables are presented in Table 3.

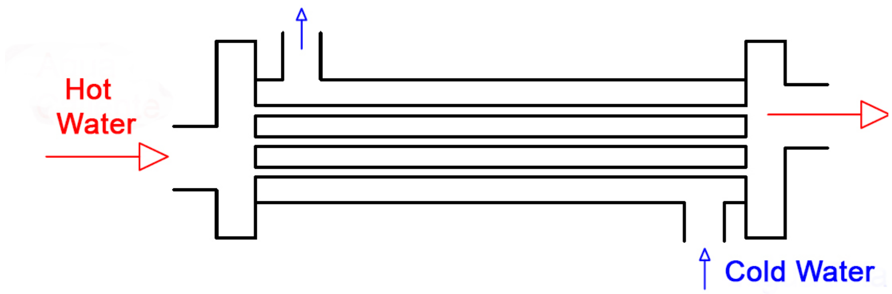


Figure 2: Direction of the flows in the exchanger (hot water through the tubes. Cold water through the shell, in a counter flow direction)

Table 3: Initial values for flow and temperature for the different flows.

Variable	Value
Hot water temperature	$56.5\,^0C$
Hot water flow	$3\,lmin^{-1}$
Cold water temperature	$15.3\,^0C$
Cold water flow	$3.7\,lmin^{-1}$

2.4 Experimental data collection

The *Armfield Heat Exchanger HT33* software, provided by Armfield, was used to collect the experimental data. This software allows the collection the data of temperature and flow in the exchanger in real time. A test time of 60 seconds was established; and was chosen as initial operating configuration, the values summarized in Table 3. With this configuration was mounted the heat exchanger on the *HT30XC Computer Controlled Heat Exchanger Service Module* (Armfield module, which allows the fluid that enters the exchanger to be heated, regulates the flow of hot and cold fluid and also measures temperatures and the quantities of inflow and outflow of fluids).

2.5 Simulation

The *SolidWorks*[2] software was used to simulate the heat exchange processes that take place in the device. First the three-dimensional design of the heat exchanger was obtained and then the computer simulation of heat transfer was carried out. Figure 3 shows the three-dimensional representation of the equipment.

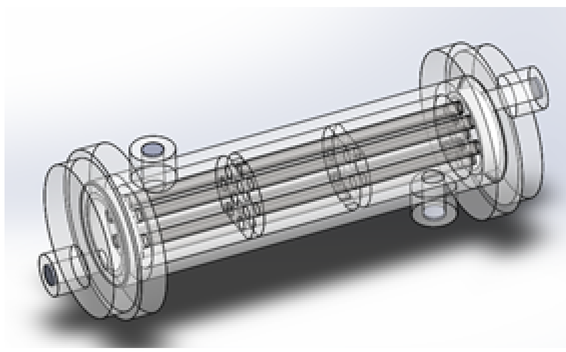


Figure 3: Three-dimensional design of the Shell and Tube Exchanger

2.5.1 Simulation parameters

The parameters that were used into the simulation software, were the flow values obtained through the real time measurement, are shown in Table 4. Three types of mesh quality were used for the simulation. The software allows automatically generate the "thick", "medium" and "fine" mesh types. The characteristics of each type of mesh are shown in Table 5.

[2]The SolidWorks software was used under license provided by Universidade Estadual Pualista "Júlio de Mesquita Filho". Garantinguetá, Brasil.

Table 4: Initial temperature and velocity values for the different flows of fluids

Time [s]	**Hot water inlet temperature** (^0C)	**Cold water inlet temperature** (^0C)	**Hot water flow** ($l\,min^{-1}$)	**Cold water flow** ($l\,min^{-1}$)
0	37,2	21,3	0,0	0,04
5	56,2	15,3	5,6	3,96
10	56,5	15,3	4,3	3,56
15	56,5	15,2	3,5	3,82
20	56,6	15,3	3,3	3,89
25	56,6	15,3	3	3,86
30	56,9	15,3	3	3,69
35	57,3	15,3	3	3,82
40	57,6	15,3	3	3,66
45	57,8	15,4	3,1	3,74
50	57,9	15,4	3	3,75
55	58	15,4	3,1	3,6
60	58,1	15,4	3,1	3,6

Table 5: Configuration of the Heat Exchanger for tests (number of mesh nodes)

Parameter	**Thick mesh**	**Medium mesh**	**Fine mesh**
Number of cells for the fluids	2534	43294	152426
Number of cells for the solids	5606	49740	190492
Number of partial cells	10792	43298	225879
Estimated simulation time (hours)	9	47	134

2.6 Mathematical model

The mathematical model that governs the operation of the exchanger is based on the energy equation (1) (see, for example, [16]):

$$\rho C_p \frac{DT}{dt} = -\nabla \cdot \vec{q} + \beta T \frac{Dp}{dt} + \Phi, \tag{1}$$

where ρ: density; C_p: heat capacity; T: temperature; t: time; q: heat flow density; β: expansion coefficient; p: pressure; Φ: volumetric dissipation.
For the case when the cold fluid flows through the shell and the hot one through the tubes, the following considerations are taken into account: heat exchange only occurs between hot and cold fluids. The temperatures and velocities of the fluids are uniform throughout the normal section in the direction of flow in the tubes. The fluids have constant physical properties, which are evaluated at the average temperature of the fluid. The changes in kinetic and potential energy are negligible, just like the axial heat transfer due to conduction. The global

coefficient of heat transfer is constant. The mass flow is constant through the tubes and shell. There is no change in the pressure drop in the system. There is no phase change of the fluids. The transitions through the exchanger occur by horizontal and vertical sections. The idealizations considered allow obtaining, from equation (1), equations (2) and (3) that describe the dynamic behavior of each part of the system:

$$m_t C_{p_t} \left(T_t^i - T_t^o\right) + FUA\left(T_s - T_t\right) = \rho_t C_{p_t} V_t \frac{T_t}{dt}, \tag{2}$$

$$m_s C_{p_s} \left(T_s^i - T_s^o\right) + FUA\left(T_s - T_t\right) = \rho_s C_{p_s} V_s \frac{T_s}{dt}, \tag{3}$$

where the subscript t refers to the tubes and the subscript s to the shell. Besides, T^i: inlet temperatures of the fluids; T^o: outlet temperatures of the fluids; F: correction factor; U: global coefficient of heat transfer; A: heat transfer area; V: fluid volume.

3 Results

3.1 Experimental

Table 6 shows the experimental results obtained by measuring outlet temperatures (for both hot and cold water), taken at 5-second intervals. As can be seen in this table, the values tend to stabilize after 20 seconds.

Table 6: Experimental outlet temperatures

Time [s]	**Hot water outlet temperature** (^0C)	**Cold water outlet temperature** (^0C)
0	35,8	18,1
5	51,8	22,1
10	51	20,8
15	51	20,3
20	50,5	19,9
25	50,5	19,8
30	50,7	19,7
35	51,6	19,8
40	51,3	19,8
45	51,3	19,8
50	51,4	19,9
55	51,6	19,8
60	51,5	19,9

The graphs in Figure 4 show the behavior of the inlet and outlet temperatures for the cold and hot water flows used in the heat exchanger. The curves confirm the tendency of the system towards stability around 20 second after beginning the test.

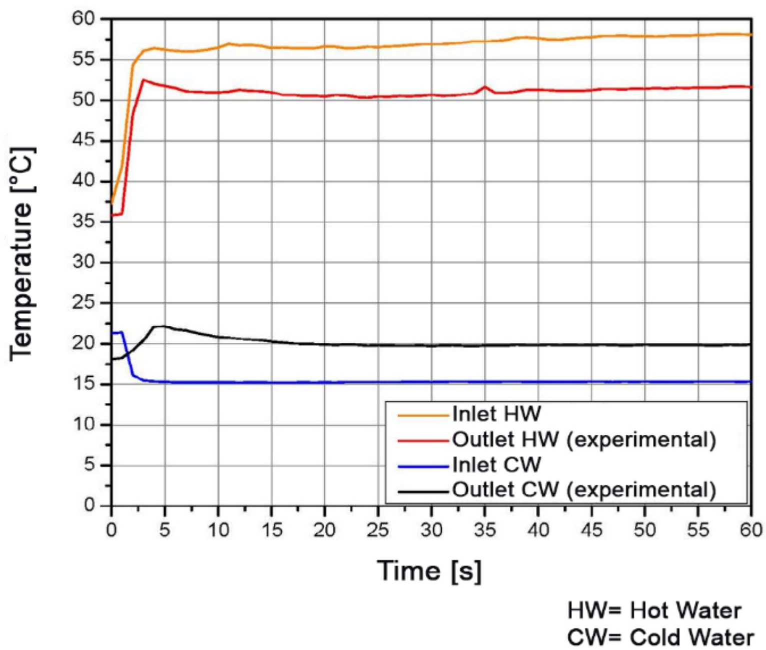


Figure 4: Experimental data of temperature vs time

The outlet temperature for hot water, compared to the inlet temperature, is for obvious reasons lower (since the flow of hot water transfers heat energy towards the flow of cold-water, which decreases the temperature of hot water at the exit). The behavior curve of hot-water outlet temperature is similar to the behavior curve of hot water inlet temperature, but shifted on the axis of the ordinates. For the case of cold water, the behavior of the outlet temperature curve is inverse, i.e. the behavior curve of the cold-water outlet temperature is a kind of reflection of the inlet temperature curve. This phenomenon is because in the initial period (from 0 to 10 seconds) there is a decrease in the inlet temperature of cold water, since this temperature is lower than the temperature of the exchanger's shell. The position of the thermocouples and the initial mass of cold water will provide a higher temperature due to the heat absorption of the shell. In contrast, the outlet temperature of cold water has an upward behavior in the same initial time period because the process of heat exchange between the hot fluid and the cold fluid is slow (it is not instant, it is time dependent) . Similarly, there is a peak of the temperature value around

5 seconds, caused by the thermal inertia of the fluid, that is, the opposition to change the state. In this case, changing from one state of heat absorption, to one of stable temperature.

3.2 Computational

Table 7 shows the simulated results of outlet temperature of hot water for thick, medium and fine mesh. As shown, the temperature values are stabilized at a time, which is similar to the experimental stabilization time. Additionally, the type of mesh does not have a significant influence on the simulation results. However, a better quality of the mesh (finer) will produce results more close up to the experimental ones. Moreover, there is a peak in the outlet temperature of hot water around 2 seconds, due to the thermal inertia considered by the software.

Table 7: Simulation results (output temperatures, hot water)

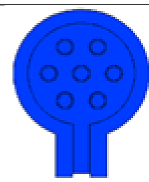
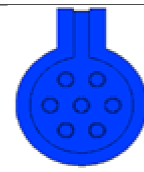
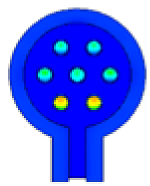
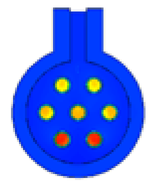
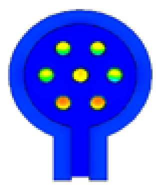
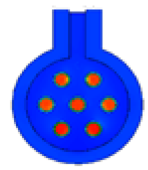
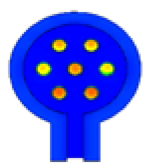
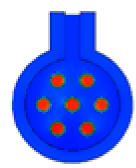
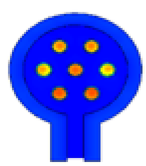
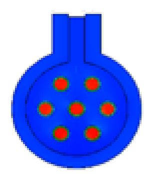
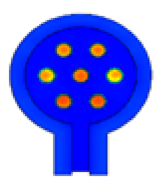
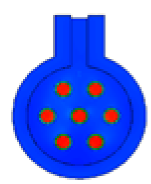
Time [s]	**Thick mesh**	**Medium mesh**	**Fine mesh**
0	18,05	18,05	18,05
5	52,08	53,08	52,63
10	51,78	52,38	52,6
15	51,51	52,11	52,55
20	51,57	52,09	52,53
25	51,59	52,07	52,51
30	51,58	52,05	52,50
35	51,58	51,98	52,49
40	51,58	51,98	52,49
45	51,58	51,98	52,49
50	51,58	51,98	52,49
55	51,58	51,98	52,49
60	51,58	51,98	52,49

Table 8 shows the results obtained for the outlet temperature of cold water and the same types of meshing. We can see a behavior that is similar to the previous case, now the temperature values with medium and fine mesh are closer to the values obtained experimentally. Similarly, at the beginning of the process, the values obtained with those meshes, show a similar behavior to the one demonstrated experimentally. Not so for the thick mesh.

Table 8: Simulation results (output temperatures, cold-water)

Time [s]	**Thick mesh**	**Medium mesh**	**Fine mesh**
0	18,05	18,05	18,05
5	19,39	19,68	19,86
10	19,29	19,53	19,78
15	19,18	19,51	19,75
20	19,18	19,49	19,74
25	19,18	19,47	19,73
30	19,18	19,47	19,71
35	19,18	19,47	19,71
40	19,18	19,47	19,71
45	19,18	19,47	19,71
50	19,18	19,47	19,71
55	19,18	19,47	19,71
60	19,18	19,47	19,71

The heat transfer process is shown in Figure 5 that appears later, which shows how the temperature varies according to time. The transverse sections correspond to the location of cold-water inflow and outflow; the images were obtained from the data with fine mesh. In the first section, in the bottom part where there is inflow of cold water, the temperature of hot water is not the same in all the tubes of the exchanger. This is due to the position of the fluid inlet point, which, when displaced downwards, will lose heat as it moves farther until it reaches the upper tubes. As time progresses, a difference in temperature can be seen in each of the tubes. That is, a lower fluid temperature at the bottom of each tube, due to the position of the cold-water inlet, since the first contact surface is the bottom of each tube. At the height of the twelfth, it is now possible to see, thanks to changes in color tone, how the heat transfer caused by the temperature gradient occurs. It is also possible to see that as time progresses; temperatures stabilize, and acquire a more homogenous tone. In addition, it is possible to appreciate the points where there is greater transfer of heat between the walls of the tubes and the fluid.

Time[s]	Cold water intake	Cold water outlet
0		
2		
4		
6		
8		
10		

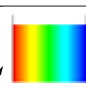
$56,5\ ^0C$  $15,5\ ^0C$

Figure 5: Simulated behavior of inlet and outlet temperatures of cold-water

3.3 Comparison of results

The comparison between the experimental and simulated results allows the validation of the computational tool, that is, it describes the processes that occur in the heat exchanger with a good level of accuracy. The graph of Figure

6 shows the hot water, experimental and simulated temperature curves with the different types of mesh. It is possible to appreciate the similarity between them, as well as for the equilibrium values. The variations observed in the experimental curve are attributable to several factors, such as the accuracy of measuring instruments, heat losses in pipes and fittings, impurities in the fluid and the inertia of the fluid that resists a status change. After 50 seconds, the equilibrium values are similar.

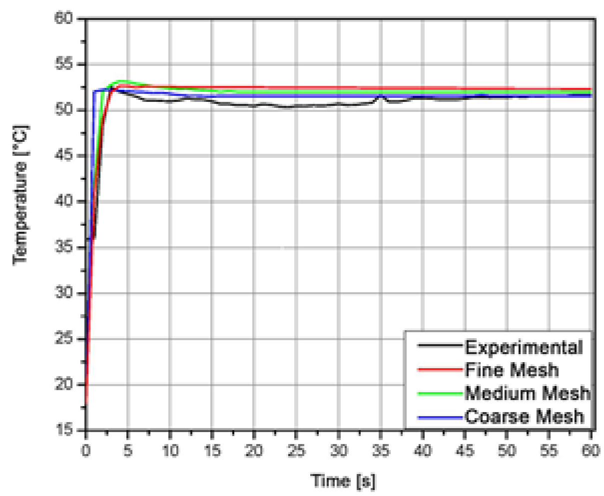


Figure 6: Behavior curves for outlet temperatures, hot water (simulated and experimental)

The comparison of results for the cold-water outlet temperature curves is shown in Figure 7. In this case, there is also a similarity between them, and the temperature equilibrium values are similar with a tolerance of $\pm 0,5\,^0C$. For the experimental curve, the temperature increase occurs a few seconds later than for the simulated ones. Once again, the factor that influences that most is the thermal inertia of the fluid. As in the case of hot water, it is possible to see the effect of better meshing, especially at the beginning of the process. At the beginning of the process, the experimental curve has a peak at about 5 seconds, as opposed to the simulated curves. This behavior is explained by the characteristics of a heat transfer process, for which the temperature requires some time to stabilize.

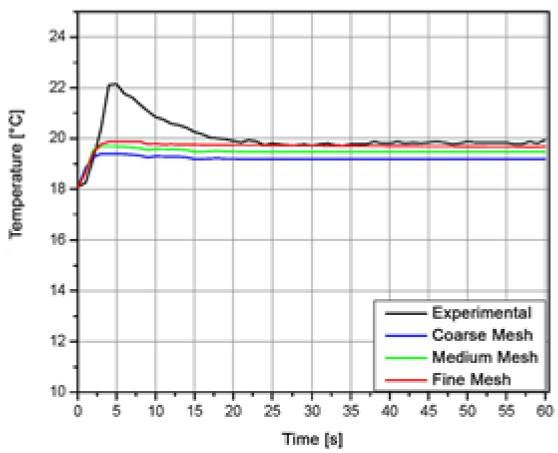


Figure 7: Behavior curves for outlet temperatures, cold water (simulated and experimental)

In general, both the experimental and the simulated results have similar behaviors and stabilize at similar times. The maximum percentage of relative error between the experimental and computational data of the exit temperature for hot water, if analyzed from the moment of stabilization of the process (20 seconds after it started), is approximately 4%, and is obtained for the fine mesh. While the same error for the cold-water outlet temperature is approximately $3,62\%$ for the thick meshing.

4 Conclusions

The outlet temperature curves for hot and cold water have similar tendencies for the experimental and the simulated data, therefore is validated the computational tool used to simulate the operation of the exchanger. The values obtained are coherent with the tolerances recorded in previous research. For example, in [8] with a numerical solution of the mathematical model that describes the operation of the exchanger, under certain conditions a tolerance of 10% is reached; however, the maximum relative error in the simulation proposed in this work, also under certain conditions (temporary in this case), does not exceed 5%. The result obtained is also comparable, in terms of deviation, with that obtained by the authors in [7]. Therefore, when there is any situation that hinders the use of the heat exchanger in the thermo-fluids laboratory, it is possible to continue the laboratory practices and the normal course of lessons by applying the simulation. Additionally, the simulation technique becomes an educational tool to predict behaviors of the temperature curves in the exchanger when the conditions or initial data go beyond the established ranges for the laboratory exchanger.

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