

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-2424

CONSTRUCTION OF A SERPENTINE-TYPE HEAT EXCHANGER AND ANALYSIS OF THERMAL EFFICIENCY

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Abstract. *The objective of the article was to create a serpentine heat exchanger to reduce the temperature of the air using cold water. The system consisted of a cooper coil that received cooled water and performed the exchange of heat with the air in a room with a high degree of insulation. In thermal analysis, the overall heat transfer coefficient will be determined. It is expected to demonstrate that the heat transfer coefficient of the gases has a low value when compared to liquids. An alternative to increase the performance of the chalk changer would be to use finned coils, since they increase the area of heat exchange significantly.*

Keywords: *heat exchanger, serpentine, heat transmission*

1. INTRODUCTION

Heat exchanger is a device capable of performing the transfer of heat between one or more fluids that are at different temperatures. Its purpose is to cool or heat fluids using a circuit that promotes thermal exchange between them (Incropera, 2007).

There are numerous applications of heat exchangers in day today life. For example condensers and evaporators used in refrigerators and air conditioners. In thermal power plant heat exchangers are used in boilers, condensers, air coolers and chilling towers etc. Similarly the heat exchangers used in automobile industries are in the form of radiators and oil coolers in engines. Heat exchangers are also used in large scale in chemical and process industries for transferring the heat between two fluids which are at a single or two states (Feng, 2012).

There are several types of heat exchangers. In most of them, fluids are separated by a metal surface and can be classified according to their geometry, heat transfer mechanisms, direction and direction of fluid streams and the type of process (Zoghbi Filho, 2004). The serpentine type heat exchanger consists of one or more coils arranged in a tank and are generally cylindrical or flat tubes (Limberger, 2013; Mello, 2000).

The heat transfer rate in this type of exchanger has the advantage of being able to accommodate a large surface in a small space. Therefore, they are an alternative in situations where space is limited and end up being highlighted in relation to the straight tube changers (Aziz and Sedahmed, 2010; Silva Júnior, 2015).

According to Khairul et al. (2013), quoted by Ferreira (2015), there is still a secondary contribution to the process of heat transfer in the coil: due to centrifugal forces, a spiral flow is created, inducing a second flow pattern, consisting of two vortices perpendicular to the direction of the axial flow and, with this, the process of heat transfer occurs by diffusion in the radial direction, as well as by convection.

From this perspective, it can be seen that serpentine heat exchangers have fundamental importance in several areas of engineering and one of the major concerns of designers and engineers has been to conduct research to ensure increasingly efficient projects to improve thermal performance.

Therefore, based on the information present in the literature, this work aimed to design and construct a serpentine-type heat exchanger, in addition to performing a thermal analysis of the fluids used in the device.

2. MATERIALS AND METHODS

The materials used in the manufacture of the heat exchanger were: Aluminum coil, Copper coil, Connection hoses between the exchangers, K7 drain pump, polyurethane box and Exhaust fan. The figure 1-a and 1-b show the components in the heat exchanger assembly.



Figure 1. (a) Elements of the heat exchanger. (b) Exhaust fan used to generate airflow.

The execution of the heat exchanger can be divided into two stages. In the first, a fluid (water) at room temperature (approximately 26°C) enters the aluminum coil, in which it is immersed in water at low temperature (water at 0°C), thus providing a first heat transfer.

Subsequently, the cooled water exits the aluminum coil and enters a copper coil, which is inserted in a box of polyurethane, material of high degree of thermal insulation. An engine then injects air into the polyurethane box, where there is a second heat transfer, this time between the cooled water and the air.

Finally, the water from the copper coil leaves the polyurethane enclosure through a hose and passes through a pump, whose function is to return the water to the aluminum coil, causing the system to start over.

After the equipment was assembled, the system was turned on for a few minutes to perform the thermal analysis of the system. The heat transfer analysis was performed only in the section between the cooled water and the air (in the polyurethane box).

In the analysis of heat exchangers, several thermal resistances are involved between hot and cold fluids, called the global heat transfer coefficient (U). Basically, the set of thermal resistances for coils is constituted by:

- Resistance between the inner surface of the tube and internal fluid (convection);
- Tube wall conduction resistance;
- Resistance between external surface and external fluid.

With these values, it becomes possible to calculate the overall coefficient of heat transfer.

Another parameter used in the analysis in heat exchangers is the effectiveness of their operation. In this study, we used the effectiveness method and NTU.

It has been considered that the outer surface of the heat exchanger is perfectly insulated so that there is no loss of heat to the surroundings, and any heat transfer occurs only between the two fluids.

3. MATHEMATICAL EQUATIONS

The heat flow through convective water passes through the wall of the copper tube by conduction and flows into the air by convection. According to the equations described in ÇENGEL (2009) the thermal resistance of the heat flux in series is given by Eq. (1):

$$R = R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi k L} + \frac{1}{h_o A_o} \quad (1)$$

Where R is the resistance, h is the heat transfer coefficient, A is the area, L is the length, D is the diameter and k is the thermal conductivity. The indices i , o and wall mean respectively inside, on the wall and outside the tube.

Figure 2 shows schematically the heat transfer through the wall of a tube and the resistance analysis:

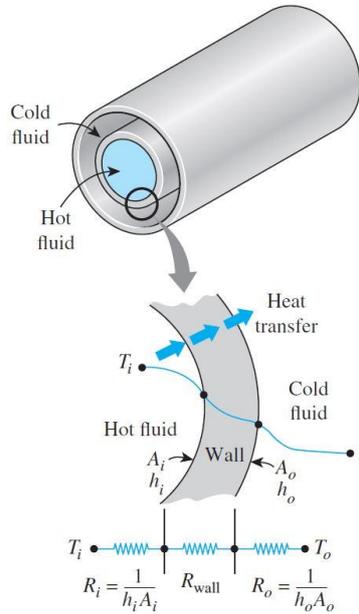


Figure 2. Thermal resistance of the heat flux (Çengel, 2009).

According to the equations described in ÇENGEL (2009), the overall heat transfer coefficient is related to the heat flux according to Eq. (2) and (3):

$$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T \quad (2)$$

$$R = \frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} \quad (3)$$

Where \dot{Q} is the heat transferred per unit time, ΔT is the temperature difference and U is the global heat transfer coefficient.

As it is a tube of very small thickness with respect to its length, the areas A_i and A_o are considered the same. Since the thermal conductivity of copper is very high, the thermal resistance term referring to conduction approaches zero (Çengel, 2009). Thus, the equation of the global coefficient becomes Eq. (4):

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o} \quad (4)$$

In order to determine the global coefficient of heat transfer, it is necessary to obtain the convection coefficients of water (h_i) and air (h_o). As it is a heat exchanger, the type of flow commonly found on the outside of the pipes is a perpendicular cross flow on a pipe bank. This type of flow is taken into account that the flow pattern is affected by the turbulence created by the air flow over the tubes.

Pipe benches are usually organized in line or staggered. In this experiment, the in-line configuration was used. Different from the analysis done in an external flow in a single tube that uses the speed of the fluid in contact, in the configuration of tube bank the analysis is made from the maximum speed, that in the line arrangement, it occurs in the minimum area of flow between the tubes according to the following by Eq. (5):

$$V_{max} = \frac{St}{St-D} V \quad (5)$$

Where St is the vertical distance between the centers of the tubes located in the first row, D the diameter of the tubes and V the velocity of entry of air into the heat exchanger (Çengel, 2009).

Another important factor in the tube bank analysis is the correction factor of the Nusselt number, but it is only used for banks with 16 or less tubes, so it does not influence the result since the heat exchanger of this experiment has 17 tubes.

Thus, the calculation of the Reynolds number for this flow is given by Eq. (6):

$$Re = \frac{v_{max}D}{\nu} \quad (6)$$

Since the configuration of the tube bank is in-line and the Reynolds number is between 1000 and 200000, through Table 7-2 of the Çengel (2009), the experimental formula for obtaining the Nusselt number is given by Eq. (7):

$$Nu = 0,27 \cdot Re^{0,63} \cdot Pr^{0,36} \cdot \left(\frac{Pr}{Pr_s}\right)^{0,25} \quad (7)$$

Where Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number of the fluid in the inlet and Prs is the Prandtl number of the mean fluid temperature.

With the Nusselt number is possible to obtain the convection coefficient of air through Eq. (8):

$$h_o = \frac{kNu}{D} \quad (8)$$

In the case of water, the flow is internal and the fluid undergoes heat transfer by forced convection. In the analysis made in this heat exchanger, the hypothesis was assumed that the surface heat flux is constant. Since the Reynolds number is in the laminar flow range, the Nusselt number is constant and, thus, the convective heat transfer coefficient (hi) is given by Eq. (11).

The analysis for water (internal forced convection) is given by Eq. (9), (10) and (11):

$$Re = \frac{VD}{\mu} \quad (9)$$

$$Nu = \frac{hD}{k} \quad (10)$$

$$hi = \frac{kNu}{D} \quad (11)$$

Another parameter used in the analysis in heat exchangers is the effectiveness of their operation. A widely used method is the effectiveness and NTU method. This method replaces the LMTD, in which several iterations are required in order to obtain the result. Eq. (12) and (13) demonstrate the NTU procedure (Çengel, 2009).

$$\dot{Q} = C_c(T_{c,saida} - T_{c,entrada}) = C_h(T_{h,entrada} - T_{h,saida}) \quad (12)$$

$$\dot{Q}_{max} = C_{min}(T_{h,entrada} - T_{c,entrada}) \quad (13)$$

Where C is the specific heat and the indices h and c indicate the hot and cold fluids respectively. \dot{Q} is the actual heat transfer rate of the analyzed fluid and \dot{Q}_{max} is the maximum possible heat transfer rate in a heat exchanger and occurs when the cold fluid is heated to the inlet temperature of the hot fluid, this should be analyzed through the fluid with lower thermal capacity, as it will suffer the greatest temperature change. Thus, it is possible to obtain the effectiveness of the heat exchanger analyzed in this experiment, observed in Eq. (14):

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \quad (14)$$

Where ε is the effectiveness of the heat exchanger. By the values obtained experimentally, the water is the fluid with less thermal capacity, since its mass flow is much inferior with respect to the air. Thus, the effectiveness analysis will be:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_{min}(T_{s,water} - T_{e,water})}{C_{min}(T_{e,air} - T_{e,water})} = \frac{T_{s,water} - T_{e,water}}{T_{e,air} - T_{e,water}} \quad (15)$$

Ts,water and Te,water are respectively the outlet and inlet temperatures of the water in the heat exchanger and Te,air the inlet temperature of the air in the heat exchanger.

Using the effectiveness value, it is possible to find the heat exchanger NTU. Since the heat exchanger type is shell-and-tube, a relationship between NTU and effectiveness is given in Eq. (16).

$$NTU = -\frac{1}{\sqrt{1+c^2}} \ln \left(\frac{2/\varepsilon - 1 - c - \sqrt{1+c^2}}{2/\varepsilon - 1 - c + \sqrt{1+c^2}} \right) \quad (16)$$

Where $c = \frac{c_{min}}{c_{max}}$

With the NTU value, it is possible to find the heat exchange surface area by Eq. (17).

$$NTU = \frac{U \cdot A_s}{c_{min}} \quad (17)$$

4. RESULTS

Table 1 shows the data used to set the heat exchanger in operation:

Table 1. Initial measurements

Fluid	Input Temperature (°C)	Output Temperature (°C)	Flow Rate (Kg/s)	Thermal Capacity (kJ/kgK)
Water	0,5	8,0	0.00686	0.0288
Air	24,0	20	0.10655	0.1072

Based on the values initially measured, it was possible to determine some properties for both air and water that will be important in the following calculations.

Table 2. Properties for the air and water

Fluid	Specific mass - ρ (kg/m ³)	Prandtl Number - Pr	Thermal conductivity - k (W/mK)	Volumetric flow rate - Q (m ³ /h)
Water	999,8	13.5	0.561	236,5
Air	1.1839	0.7296	0.02551	-

The heat exchanger has 17 copper tubes with the outside diameter (D) of 6.39 mm.

Table 3. Values for the air.

Heat exchanger air inlet velocity (V)	8.36 m/s
Maximum velocity (Vmax)	10.91 m/s
Reynolds number (Re)	44631.82
Prandtl number (Pr)	0.7296
Prandtl number of the mean fluid temperature (Prs)	0.73038
Nusselt number (Nu)	203,97
Convection Coefficient (h ₀)	814.28 W/m ² K

Table 4. Values for the water.

Absolute viscosity (μ)	1,004 x 10 ⁻⁶ m ² /s
Velocity (V)	0,214 m/s
Reynolds number (Re)	1362.4
Nusselt number (Nu)	4.36
Convection Coefficient (h _i)	382.74 W/m ² K

Table 5. Results obtained.

Effectiveness	32 %
NTU	0.407
Overall coefficiente (U)	260.36 W/m ² K
Surface area (As)	45.02 mm ²
Heat flow (Q)	0,6768 kW

5. CONCLUSIONS

Based on the study performed, it can be highlighted the following points: Although all experiments were done empirically, only with the knowledge acquired in the area of thermosciences, the obtained values were acceptable. For effectiveness the value of 32 % it was considered satisfactory. In the execution of the serpentine type heat exchanger prepared in this report, it was a obtained a high thermal efficiency between hot and cold water in the first section of the design and a lower efficiency in the polyurethane enclosure section between cold water and air. Because the gases have low coefficient of heat transfer when compared to fluids, the decrease in air temperature was not as effective when compared to the first section of the design. One way to improve heat transfer in the second section would be to use finned coils and thereby increase the heat exchange area. It is suggested to carry out new tests, subsequent to the modifications proposed in the prototype, in order to improve the performance of the project.

The final result corresponded to the project expectation, considering that the study of heat exchangers liked to the search for improvements in its effectiveness has impact on both the academic community and the industry. A suggestion for an improvement in the system would be to insert a return air mechanism, after passing through the exchanger, air would return to the fan inlet to pass thought the exchanger at a lower temperature, thereby improving system throughput.

6. REFERENCES

- Aziz, M., Mansour, I. and Sedahmed, G., 2010. Study of the rate of liquid–solid mass transfer controlled processes in helical tubes under turbulent flow conditions, *Chem. Eng. Process - Process Intensification*, Vol. 49, No. 7, pp. 643-648.
- Çengel, Y.A., 2009. *Transferência de Calor e Massa: Uma Abordagem Prática*, Editora McGrawHill, 3^a edition.
- Feng, Y.M., Lin W.C., Chieng, C.C., 2012. Numerically investigated effects of different Dean number and pitch size on flow and heat transfer characteristics in a helically coil-tube heat exchanger, *Applied Thermal Engineering*, Vol. 36, pp. 378-385.
- Ferreira, T.P.A., 2015. *Projeto e Construção de um trocador de calor: uso de nanofluidos (nanopartículas de outro em fluido base) como líquido de arrefecimento*, Monography (University Graduate), Universidade Tecnológica Federal do Paraná, Ponta Grossa, Brasil.
- Incropera, Frank P., 2008. *Fundamentos de transferência de calor e de massa*. LTC, Rio de Janeiro, 6 edition.
- Limberger, Rodrigo Prestes, 2013. *Sistema de resfriamento de mosto de cerveja em processos artesanais*. 2013. Monography (University Graduate), UFRGS, Porto Alegre, Brasil.
- Mello, Richard Garcia Alves de. *Modelo de simulação e análise teórico-experimental de serpentinhas resfriadores e desumidificadores de ar*. 2000. Dissertação (Mestrado em Engenharia Mecânica), Escola de Engenharia de São Carlos, University of São Paulo, São Carlos, Brasil. 12 mar. 2018 <<http://www.teses.usp.br/teses/disponiveis/18/18135/tde-07042017-105336/pt-br.php>>.
- Silva Júnior, J.A., 2015. *Análise de um trocador de calor tipo serpentina de uma planta de hipoclorito de sódio*. Monography (University Graduate), Universidade Estadual Paulista, Guaratinguetá, Brasil. 22 Jun. 2019<<http://hdl.handle.net/11449/139259>>.
- Zoghbi Filho, J.R.B., 2004. *Avaliação teórico/experimental do desempenho termo-hidráulico do ar em trocadores de calor tipo serpentina*, Ph.D thesis, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brasil. 12 mar. 2018 <<https://bv.fapesp.br/pt/dissertacoes-teses/115027/avaliacao-teoricoexperimental-do-desempenho-termo-hidraulic>>.

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