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MODELING AND COMPARATIVE STUDY OF A COMPACT HEAT EXCHANGER WITH EXTENDED SURFACES

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Abstract. *The optimization of industrial processes for maximum utilization of available energy has been a line of scientific research quite widespread recently. Many industrial applications require the use of heat exchangers with piped fittings, whether or not finned, operating in air conditioning, refrigeration, heating, radiators and in various other engineering applications. In this work, the theoretical formulations are related to the effects of modes of heat transfer in a compact heat exchanger. Through these formulations, it was possible analyze what material (Cu, Al) would be more thermally efficient and relate the theories of heat exchangers to those of extended surfaces and to analyze the contributions of these effects on the heat transfer rates and the efficiency of these surfaces. Thus, a computational code was developed in the Engineering Equation Solver (EES) platform to size, model the compact heat exchanger. On the basis of the data submitted, it was found that the Cu fin is more efficient thermally about Al this may be explained because the higher thermal conductivity of copper. As comparisons between the settings of the heat exchanger with copper pipes in the presence and absence of fins it was observed that there is a reduction in the area of heat exchange without fins, however with the attachment of the extended surface occurs an increase in global heat transfer area.*

Keywords: *Energy, Compact Heat Exchanger, Extended Surface.*

1. INTRODUCTION

Centuries ago mankind is dedicated to the study of heat, ranging from simple phenomena as the evaporation of rainwater, the expansion of mercury in a thermometer on contact with the skin of a patient, burning a breeze Sea in a coastal town, even more complex phenomena, like theories of entropic expansion of universal stars.

In engineering there are numerous applications of thermal energy, these depend exclusively on the characterization of heat as the form of energy that can be transferred from one system to another as a consequence of the temperature difference between them. The most important are the thermal machine design and thermal systems, such as combustion engines, turbines, air conditioners, refrigerators and steam engines, which are designed based on heat transfer analysis. Early scientific efforts were concentrated on understanding the phenomena of nature and the development of mathematical theories to describe the generation and transfer of heat in physical systems. (Bejan, 2013).

However, there are some problems caused by the generation of heat, such as: overheating of motors with loss of power, collapse of lift structures by expansion excessive force of the abutments, loss of efficiency of the cutting tools in machining, and the degradation of machinery or components there of in operation with the wear and tear of its constituent materials, can negatively influence the performance of electronic processors, culminating in a greater consumption of electric energy, besides generating human discomfort (Nosko, 2019).

In addition, for Cengel and Ghajar (2009), the generation and transfer of heat may be desired in some engineering applications. For example: in industrial processes with heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators and solar collectors, test materials, generation and distribution of power, and in manufacturing and finishing processes in that the high heat rates are induced to increase the efficiency of the processes of production and in the steel mill.

Many researchers have devoted themselves to the study of heat transfer in diverse areas of knowledge and practical applications in engineering, besides having developed various methods to treat problems related to this form of energy (Bluck and Wolfendale (2017); Nasiri and Enzinger (2019)). Among them is the classical theory (CT), which corresponds to the analytical solution of the problems of heat transfer in continuous systems through the mechanisms of heat transfer, that is, the use of the fundamental laws of thermodynamics in conjunction with the transfer modes (conduction, convection and radiation), whose governing equations are partial differential equations.

In this context, this researcher the heat transfer phenomenon in a compact heat exchanger of plate-finned tubes was studied because of the vast mechanical engineering application.

2. METODOLOGY

This research adapts the methodology and the fundamentals presented in Gregory Nellis (2009), Pábon *et al.* (2014) and Nithiarasu *et al.* (2016) for compact heat exchangers used in vehicles (radiator) and their implications, in addition to using all the fundamentals of classical theory for the design of the uncooled cross-flow heat exchanger.

The materials used in the design and modeling were copper and aluminum, since these metals are the most used in the market, for the manufacture of heat exchangers due to their low weights, corrosion resistance, durability and mainly, its high thermal conductivities (k), being that of copper, $k_{Cu} = 398.7$ W/mK superior to that of aluminum with $k_{Al} = 237.1$ W/mK. These comparisons were made in relation to the overall coefficient of heat transfer, efficiency and effectiveness of the fin when present.

The results obtained for all the proposed configurations of the compact heat exchanger (CHE) will be compared:

- compact heat exchanger without fins varying the material of the tubes;
- compact heat exchanger with and without fins keep the material of the tubes;
- compact heat exchanger with fins varying the fin material.

For problems involving compact heat exchangers, claim it is necessary to work the method of effectiveness. Cengel and Ghajar (2009) claim it is necessary to work the method of effectiveness. This allows an analysis of heat exchangers when output temperatures of the fluids are not known. The effectiveness of a heat exchanger is defined as the ratio between the actual heat transfer rate and the maximum heat transfer rate possible.

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} \tag{1}$$

The maximum possible heat transfer would occur in a counter current heat exchanger with infinite length (L),when one of the fluids try to greater temperature variation as possible.

$$\Delta T_{max} = T_{H(in)} - T_{C(in)} \tag{2}$$

When $C_c < C_h$, the cold fluid would experience the greatest temperature variation and, like $L \to \infty$, it would be heated to the temperature of the hot fluid $(T_{H(out)}) = (T_{H(in)})$ then:

$$\dot{Q}_{max} = C_{min}(T_{H(in)} - T_{C(in)}) \tag{3}$$

Where C_{min} is the lowest of C_c and C_h. The effectiveness, which is dimensionless, is in the range $[0, 1]$. It is quite useful, since if $T_{H(in)}$ and $T_{C(in)}$ are known, the actual heat transfer rate can be determined immediately by the expression:

$$\dot{Q} = \varepsilon\dot{Q}_{max} = C_{min}(T_{H(in)} - T_{C(in)}) \tag{4}$$

The Number of Transfer Units NTU is a dimensionless parameter widely used in the analysis of heat exchangers, and is defined by:

$$NTU = \frac{UA}{C_{min}} \tag{5}$$

Relationships between effectiveness and NTU can be obtained analytically for several types of heat exchangers, resulting in equations available in the literature. The equation of effectiveness ratio for cross-flow with both unmixed fluids is below.

$$\varepsilon = 1 - exp\left[\frac{NTU^{0.22}}{c}(exp(-c \cdot NTU^{0.78}) - 1)\right] \tag{6}$$

With this method it is possible to determine the heat transfer rates and output temperatures of the hot and cold fluids to mass flows of fluids and temperatures prescribed input, when the type and the size of the heat exchanger are specified. As far as the analysis regarding the compact heat exchanger with finned surfaces, this was accomplished with the classical theory of validity of fins, which is modeled by Eq. (7).

$$\epsilon_{(fin)long} = \frac{\dot{Q}_{fin}}{\dot{Q}_{without(fin)}} = \frac{\sqrt{hpkA_{ts}}(T_{base} - T_{\infty})}{hA_{fin}(T_{base} - T_{\infty})} = \sqrt{\frac{kP}{hA_{base}}} \tag{7}$$

Based on Eq. (7) it was possible to calculate the heat transfer rate to the heat exchanger with extended surfaces, this is expressed by the Eq. (8).

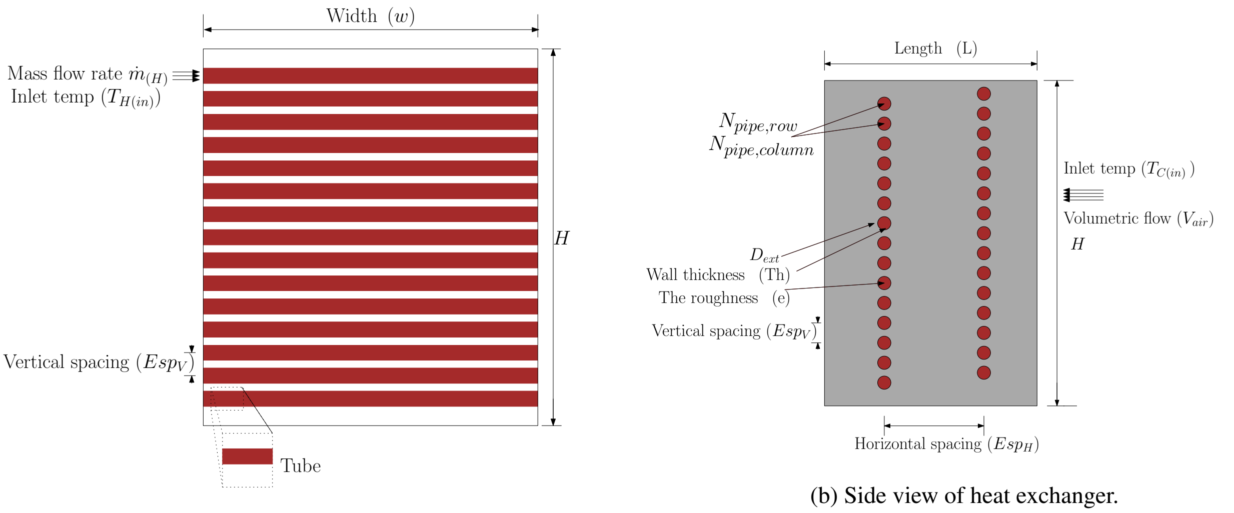
$$\epsilon_{fin} = \frac{\dot{Q}_{fin}}{\dot{Q}_{without(fin)}} = \frac{\dot{Q}_{fin}}{hA_{base}(T_{base} - T_{\infty})} \tag{8}$$

3. RESULTS AND DISCUSSIONS

3.1 Compact heat exchanger without fins

For the sizing of the heat exchanger were used the equations in the method of effectiveness, presented in detail in Cengel and Ghajar (2009), these and the thermodynamic properties of water and air were implemented and extracted, respectively from a computational code in software EES (Engineering Equation Solver).

From this, the modeling of a compact heat exchanger cross-flow water-air with both fluids unmixed and in permanent regime, the height of the front face of this heat exchanger is $H = 260$ mm and the width of the front face of the heat exchanger is $w = 200$ mm, respectively. Fifteen rows of tubes ($N_{pipe,row} = 15$) in two columns ($N_{pipe,column} = 2$) are arranged in series. The vertical and horizontal spacing between adjacent pipes are $Esp_V = 25.4$ mm and $Esp_H = 22$ mm, respectively. The length of the heat exchanger in the direction of the air flow is $L = 90$ mm. The pipes are made of copper with an external diameter of $D_{ext} = 10.5$ mm and wall thickness $Th = 0.7$ mm. The roughness of the inner surface of the tube is $e = 1.0$ μm. Cooling water enters the pipe with a mass flow rate $\dot{m}_H = 0.05$ kg/s and inlet temperature $T_{H(in)} = 90$ °C. The dry and clean air is forced to flow through the heat exchanger perpendicular to the pipes, that is, in a crossover flow and with a volumetric flow rate $\dot{V}_{Air} = 0.64$ m^3/s. The air inlet temperature is $T_{C(in)} = 20$ °C and the air is in atmospheric pressure. It is observed in Fig. 1.a and in Fig. 1.b.



(a) Front view of the heat exchanger without fins.

(b) Side view of heat exchanger.

Figure 1. Heat exchange views without fin.

The performance criterion of NTU effectiveness has been chosen to determine heat transfer rates and hot and cold fluid output temperatures for mass flows of fluids and inlet temperatures that are in acceptable ranges (Gregory Nellis, 2009).

Besides that, according Pábon *et al.* (2014) the type and size of the heat exchanger, here studied and dimensioned, is characterized as a vehicular radiator. Table 1 presents the data obtained in the modeling of the heat exchanger without fin. For convenience and compatibility, the temperature units used in the tables are in absolute temperature range.

Observing the data in Table 1, and tracing a quick comparison between the tubes made of copper and the tubes made of aluminum, there is no difference in the values of the effectiveness (ε) and the NTU values. This unchanging is also reflected in the output temperatures of the hot fluids ($T_{H(out)}$) and cold ($T_{C(out)}$), since it is through the method of effectiveness, NTU, that finds such values of output temperatures, since at the beginning of the proposed problem they were unknown.

The unit value of the overall and unit efficiency of the fins in Tab. 2 corresponds to the absence of fins in the exchanger, so these fins are considered to be isothermal and have no influence on the heat exchange, as observed in the null value of the extended surface area (fin).

It is also worth noting that even small changes in the values of the global heat transfer coefficient (UA) and the heat rate $(\dot{Q})$ caused by the data in Tab. 3, mainly the thermal conduction resistance in the wall of the pipe (R_{cond}), which is affected exclusively by the change in the material of manufacture, that is, the value of the thermal conductivity of copper to that of aluminum.

Finally, it should be noted that the resistance due to the external convection (R_{ext}), the resistance due to the internal convection (R_{int}) and the resistance due to incrustation (R_{inc}) do not change, because they are not affected by the thermal conductivity of the tube material.

Table 1. Data obtained in modeling without fin.

Radiator	ε [-]	NTU [-]	UA [W/K]	$\dot{Q}$ [kW]	$T_{C(out)}$ [K]	$T_{H(out)}$ [K]
$Pipes_{Cop}$	0.1489	0.1667	34.840	2.179	296	352.7
$Pipes_{alum}$	0.1489	0.1667	34.833	2.178	296	352.7

Table 2. Data obtained in modeling without fin.

Radiator	A_{fin} [m²]	$A_{without;fin}$ [m²]	A_{total} [m²]	η_{fin} [-]	η_{global} [-]	$\bar{h}_{ext}$ [W/m²K]
$Pipes_{Cop}$	0	0.1979	0.1979	1	1	211.7
$Pipes_{alum}$	0	0.1979	0.1979	1	1	211.7

Table 3. Data obtained in modeling without fin.

Radiator	R_{ext} [K/W]	R_{in} [K/W]	R_{inc} [K/W]	R_{cond} [K/W]
$Pipes_{Cop}$	$2.543 \cdot 10^{-2}$	$1.040 \cdot 10^{-3}$	$1.020 \cdot 10^{-3}$	$9.519 \cdot 10^{-6}$
$Pipes_{alum}$	$2.543 \cdot 10^{-2}$	$1.040 \cdot 10^{-3}$	$1.020 \cdot 10^{-3}$	$1.601 \cdot 10^{-5}$

3.1.1 Compact heat exchanger with fins

For the sizing of the unmixed water-air cross-flow compact heat exchanger with extended surfaces (fins), the fins having a thickness of $Th_{fin} = 0.33$ mm and with a distance between them of $D_{fin} = 3.18$ mm. It is observed in Fig. 2.

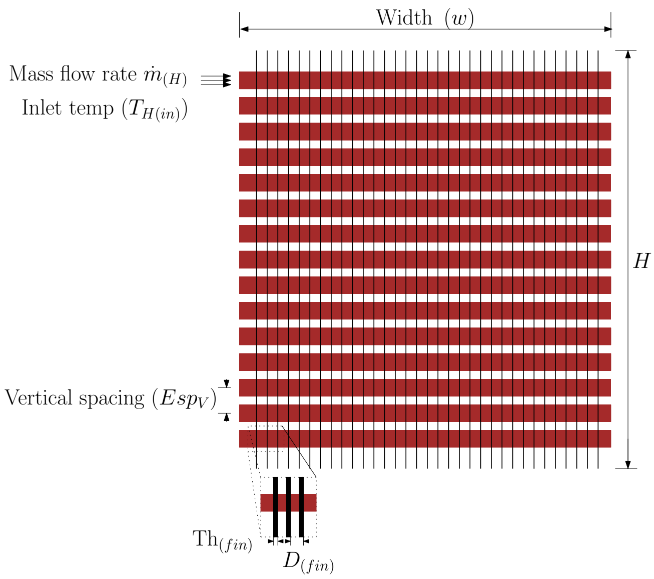


Figure 2. Front view of the heat exchanger with fins.

A comparison was made between the fins made of copper and those made of aluminum, we perceive difference in the values of effectiveness (ε) and the values NTU. These changes are also reflected in the hot fluid outlet temperatures

$T_{H(out)}$ and Cold $(T_{C(out)})$ in Fig. 3, since, through the NTU effectiveness method, these output temperature values are found.

Concomitantly, changes in the values of the global heat transfer coefficient (UA) and the heat rate $(\dot{Q})$ were also observed. This happens mainly due to the external resistance (R_{ext}) in Tab. 6, which is mainly affected by the addition of area due to the presence of fins and then by the alteration of the material of these fins, that is, by the alteration in the conductivity value thermal (k) from copper to aluminum.

In short, through Equation (2), which describes the effectiveness of the fin, it is perceived that a direct variation of the thermal conductivity changes its effectiveness. This information is according to Gregory Nellis (2009), in which it states that the thermal conductivity (k), in the association of efficiency with the design and in the selection of the fin, should be the maximum possible with respect to the material. However, the data obtained in Tab. 4, Tab. 5 and Tab. 6 do not exclude the possibility of using aluminum as is noticeable in the market, since aluminum is a lighter metal compared to copper and less costly, besides offering some protection galvanic or sacrificial when in contact with air and water.

Another expressive observation in Tab. 5 is the drop in the particular efficiency of a fin (η_{fin}) in 0.0828 or 8.28 $\%$ when changing the copper to aluminum metal, which consequently affects the overall efficiency of all fins (η_{global}) in 0.0775 or 7.75 $\%$, substantially adulterating the heat rate $(\dot{Q})$ and the temperatures $T_{H(out)}$ and $(T_{C(out)})$ of two fluids.

A satisfactory data obtained in the modeling Tab. 4 is the effectiveness of the fin in the heat exchanger with a value of ϵ = 4.272 for fins made of copper and ϵ = 4.165 for fins made of aluminum, which certifies the need for application of fins. therefore, according to Incropera *et al.* (2008), the justification criterion for the use of fins is that the effectiveness of this is, $\epsilon \geq 2$, which is obviously satisfied.

Table 4. Data obtained in modeling with fins in copper pipes.

Radiator	ε [-]	NTU [-]	UA [W/K]	$\dot{Q}$ [kW]	$T_{C(out)}$ [K]	$T_{H(out)}$ [K]	ϵ_{fin} [-]
Fin_{Cop}	0.6363	1.174	245.4	9.309	305.2	318.6	4.272
Fin_{alum}	0.6204	1.118	233.7	9.076	304.9	319.7	4.165

Table 5. Data obtained in modeling with fins in copper pipes.

Radiator	A_{fin} [m^2]	$A_{without;fin}$ [m^2]	A_{total} [m^2]	η_{fin} [-]	η_{global} [-]	$\bar{h}_{ext}$ [W/m^{2}K]
Fin_{Cop}	2.617	0.1774	2.794	0.8325	0.8431	211.7
Fin_{alum}	2.617	0.1774	2.794	0.7497	0.7656	211.7

Table 6. Data obtained in modeling with fins in copper pipes.

Radiator	R_{ext} [K/W]	R_{in} [K/W]	R_F [K/W]	R_{cond} [K/W]
Fin_{Cop}	$2.005 \cdot 10^{-3}$	$1.040 \cdot 10^{-3}$	$1.020 \cdot 10^{-3}$	$9.519 \cdot 10^{-6}$
Fin_{alum}	$2.208 \cdot 10^{-3}$	$1.040 \cdot 10^{-3}$	$1.020 \cdot 10^{-3}$	$9.519 \cdot 10^{-6}$

3.1.2 Comparisons between heat exchanger configurations with and without fins copper pipes

The data examined for configuration without fin when compared with the configuration with fin, is that there is a reduction in the area without fin,that is, the value of $A_{without;fin}$ in Tab. 2 which is 0.1979 m^2 is reduced in confrontation with the value of $A_{without;fin}$ in Tab. 5 which is 0.1774 m^2. But it should be emphasized that the reduction is pertinent, because the area available for heat exchange in the pipeline was occupied by the base of the fin, so it becomes an unavailable area.

A second interesting analysis, it is also observed in Fig. 3 the variation of the hot fluid output temperature $(T_{H(out)})$ and the cold $(T_{C(out)})$ in function of the area with fins (A_{fin}). Therefore, the analysis shows that, while changing the configuration of the exchanger without fins to the exchanger with proposed fins, there is an increase in temperature in the cold fluid, which is lower than the temperature drop in the hot fluid.

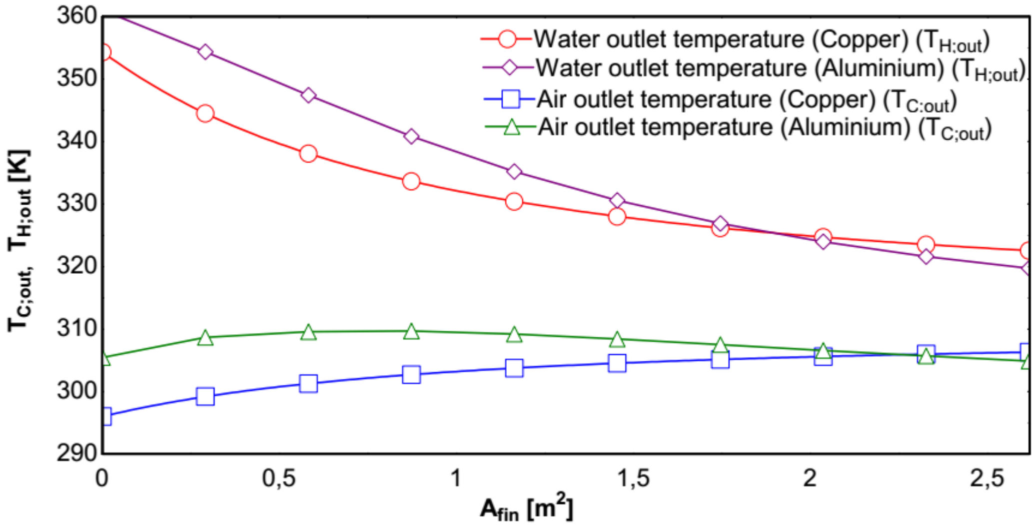


Figure 3. Fin area vs fluids output temperature.

According to the analysis, Cengel and Ghajar (2009) claims that this only occurs when the thermal capacity of the fluids at these points are different, since the specific heat of the fluids usually changes with temperature. Even so, there is a requirement of the first law of thermodynamics that the heat transfer rate of the hot fluid $(\dot{Q}_H)$ should be equal to the heat transfer rate for the cold fluid $(\dot{Q}_C)$, which is respected when observing the last two columns in Tab. 7 , thereby validating the proposed heat exchanger model.

Table 7. Data obtained in the modeling by varying the total area of fins.

Radiator	A_{fin} [m^2]	ε [-]	NTU [-]	UA [W/K]	$\dot{Q}_H$ [kW]	$\dot{Q}_C$ [kW]
$Pipes_{Cop}$	0	0.149	0.167	34.84	2.179	2.179
$Pipes_{Cop}$	0.291	0.308	0.393	82.02	4.504	4.504
$Pipes_{Cop}$	0,582	0.408	0.571	119.4	5.969	5.969
$Pipes_{Cop}$	0.872	0.475	0.714	149.3	6.954	6.954
$Pipes_{Cop}$	1.163	0.523	0.830	173.5	7.653	7.653
$Pipes_{Cop}$	1.454	0.558	0.925	193.4	8.168	8.168
$Pipes_{Cop}$	1.745	0.585	1.004	209.9	8.560	8.560
$Pipes_{Cop}$	2.035	0.606	1.070	223.7	8.866	8.866
$Pipes_{Cop}$	2.326	0.623	1.126	235.4	9.110	9.110
$Pipes_{Cop}$	2.617	0.636	1.174	245.4	9.309	9.309

In addition, in Figure (4.a), there is a comparison between the volumetric rate of air $(\dot{V_{Air}})$ ranging from 0.03 to 0.64 m^3/s with the global coefficient of heat exchange (UA) and the heat rate $(\dot{Q})$, Fig. 5, in which, while the volumetric rate is increased by $(\dot{V_{Air}})$, it becomes notorious that the configuration with fins represented by the curve in blue color, presents for the same flow, a higher overall coefficient of transfer and a higher heat rate, consequently a much higher performance in confrontation with the non-fins configuration, represented by the curve in the red color, which reinforces and justifies the need for the extended surface (fin) in the proposed heat exchanger model.

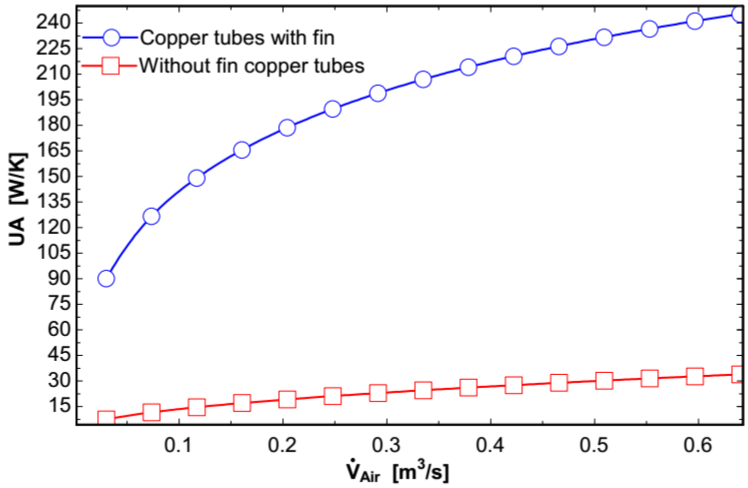


Figure 4. volumetric air rate vs global coefficient.

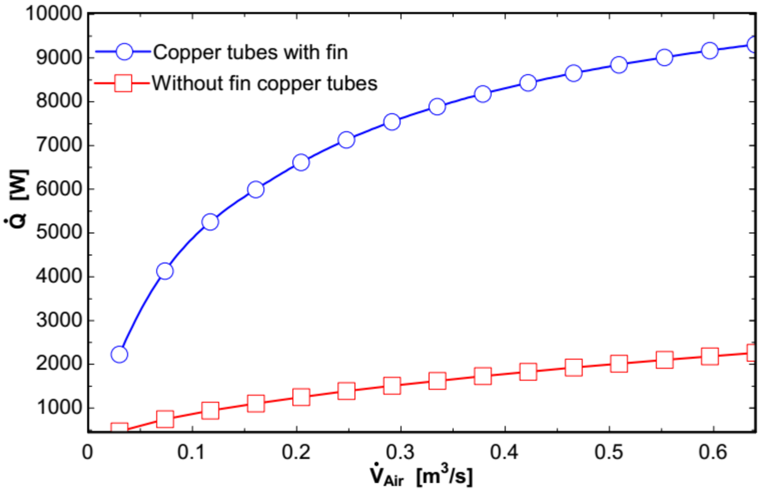


Figure 5. volumetric air rate x heat rate

4. CONCLUSIONS

This research analyzed the behavior and effectiveness of the modeling of a compact heat exchanger with cross flow with absence and presence of fins (copper and aluminum pipes).

It was also argued that there was a reduction in the area available for fin-free heat exchange for the finned configuration, but that, for the proposed model, the efficiency of these fins compensated for the loss of swap space and, , this increase of fins directly influenced the effectiveness-NTU and the fluid outlet temperatures, making it necessary to compare the results of the water exit temperatures with the air output results, so that it was possible to determine until the value of the increase parameters of fin area satisfactorily influenced this heat transfer.

Therefore, among the configurations of the compact heat exchanger proposed, the one that presented the highest effectiveness, the best overall coefficient of heat transfer and transferred heat rate, was the configuration with fins made of copper with copper pipes, followed by the configuration with fins made of aluminum and copper pipes, precisely because of the change in the thermal conductivity of the fin material. However, the two presented similar results, so that the configuration with fins made of aluminum remains attractive at the lowest cost compared to copper. Observing the finless configurations with tubes made of copper and aluminum, the results are unsatisfactory for the type of compact changer proposed, making finning indispensable.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bejan, A., 2013. *Convection heat transfer*. John wiley & sons.

Bluck, M.J. and Wolfendale, M.J., 2017. “An analytical solution to the heat transfer problem in thick-walled hunt flow”. *International Journal of Heat and Fluid Flow*, Vol. 64, pp. 103–111.

Cengel, Y.A. and Ghajar, A.J., 2009. *Tranferência de Calor e Massa*. Amgh Editora.

Gregory Nellis, S.K., 2009. *Heat Transfer*. Cambridge University Press.

Incropera, F.P., Lavine, A.S., Bergman, T.L. and DeWitt, D.P., 2008. *Fundamentals of heat and mass transfer*. Wiley.

Nasiri, M.B. and Enzinger, N., 2019. “Powerful analytical solution to heat flow problem in welding”. *International Journal of Thermal Sciences*, Vol. 135, pp. 601–612.

Nithiarasu, P., Lewis, R.W. and Seetharamu, K.N., 2016. *Fundamentals of the finite element method for heat and mass transfer*. John Wiley & Sons.

Nosko, O., 2019. “Hyperbolic heat conduction at a microscopic sliding contact with account of adhesion-deformational heat generation and wear”. *International Journal of Thermal Sciences*, Vol. 137, pp. 101–109.

Pábon, L., Yurako, N. *et al.*, 2014. “Projeto e fabricação de um túnel de vento e caracterização térmica de um radiador automotivo”.

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