23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

COMPARATIVE STUDY OF PARAMETERS INFLUENCING ON THE THERMAL-HYDRAULIC PERFORMANCE OF FIN-AND-TUBE HEAT EXCHANGERS USED IN THERMAL SYSTEMS.

Cleison Henrique de Paula
Paulo Eduardo Lopes Barbieri
Centro Federal de Educação Tecnológica de Minas Gerais, 7675, Av. Amazonas, Nova Gameleira, Belo Horizonte, MG, Brazil.
e-mails: cleissonhp@yahoo.com.br, barbieri@des.cefetmg.br

Abstract. *The increase in energy demanded in all sectors of society has been a disturbing fact in the last decade, because the technological development as a whole requires a greater availability of energy. However the economic and environmental issues are always associated with the energy issue, making necessary the search for maximum use of available energy. In this context, improvement of efficiency of the equipment becomes a differentiator, as it provides a reduction of manufacturing costs and consequently energy consumption. Thus, this study aims to compare the conclusions reached by several works about certain parameters that influence the calculation of thermal-hydraulic performance of fin-and-tube heat exchangers used in thermal systems and finally provide relevant information for such equipment to be designed efficiently from the energy point of view, in other words, obtain an increase of heat transfer without adding on too much pressure loss.*

Keywords: *Heat Exchanger, Thermal Systems, Thermal-Hydraulic Performance, Finned Tube.*

1. INTRODUCTION

In any society, the economic activity, in particular industrial one, needs energy to its full operation. In the 1970's, due to the oil crisis, a framework of energy use rationalization was originated, especially in those countries whose economy had a greater dependence on oil imports, such as Brazil, which only in the 1980's began to arise attention in relation to energy waste.

Thus, from this decade, the measures for energy use rationalization were maintained, fruit of strategic and economical maturing, and an awareness of the environmental problems caused by the production, transport, conversion and energy use.

In Brazil, according to Pereira (2012), the refrigeration consumed 12.6% of all electrical energy generated. Part of this consumption is due to thermodynamic irreversibility inherent in the heat transfer processes and the refrigerant flow inside the refrigeration system components, especially the heat exchangers.

One of the main types of heat exchangers is the fin-and-tube heat exchanger, which is widely used in the fridge sector (compound by refrigeration and air conditioning) for applications of heating and cooling the air.

This equipment provides a large surface area for heat transfer on the air side, because the air has a low convective coefficient. This improvement on heat transfer in fin-and-tube heat exchangers is provided, preferably, by the use of intensification surfaces, where these can be separated into two groups. The first group consists of the extended surfaces, known as fins, which can be of (smooth) plane surface, (corrugated) wavy, slit, louver and convex-louver. The second consists of the vortex generators, which can be wing, delta winglet, wheeler and semi-dimple, among others. The increase in the heat of transfer from the air side, without increasing significantly the pressure loss, is great interest to improve the thermal-hydraulic performance of heat exchangers and thus reduce the energy consumption of refrigeration systems. In this way, this paper aims to study a set of fin-and-tube heat exchangers comparing six different types of intensification surfaces, compound of five fins types and a type of vortex generator, examining important geometrical parameters that will help to design this equipment with the best thermal-hydraulic performance.

2. ANALYSIS OF HEAT TRANSFER INTENSIFICATION SURFACES

In this topic the heat transfer of intensification surfaces under study will be presented, along with their main characteristics, which affect the thermal-hydraulic performance of heat exchangers.

2.1 Plane Fin Surface

The plane surface fin is the most known among the intensification surfaces, due to their simplicity, durability and versatility in application. Wang et al., 1996 concluded that both the Fanning friction coefficient (f) as the Colburn j factor decrease with increasing Reynolds number. For the region where the $Re_{Dc}>2000$, the Colburn j factor does not show significant change with the variation of the fin spacing (E_{ea}).

Wang et al., 1996 concluded that for $Re_{Dc}>2000$ the number of tube rows (N_f) has a very small effect on both the friction coefficient as on the Colburn j factor, but for $Re_{Dc}<2000$, the j factor varies considerably with the number of tube rows.

Wang et al., 1996 concluded that the fin thickness (E_a) has a small effect on the friction coefficient and a significant effect on the Coburn j factor for $Re_{Dc}<1000$. The effect of the fin pitch (P_a) on the Colburn j factor is insignificant for the number of tube rows (N_f) greater than or equal to 4.

Seshimo and Fujii (1991) and Wang et al., 1997 reported that the Colburn j factor increases slightly with the decrease of fin pitch (P_a).

Chen and Ren (1988), by means of oil lampblack visualization technique, studied the pattern of air flow for a fin-and-tube heat exchanger of two rows, where they concluded that the vortex from the back of the tube does not influence the heat transfer coefficient for $Re_{Dc}<7000$ when $E_{ea}/D_c<0.33$, and the fin spacing does not affect the heat transfer coefficient for $E_{ea}/D_c>0.33$.

Gray and Webb (1986) stated that the fin thickness little influences on heat transfer characteristics of fin-and-tube heat exchanger.

2.2 Wavy Fin Surface

Among the heat transfer intensification geometries, one of the most used is wavy fin (known as corrugated).

Wang et al., 1997 stated that heat transfer coefficients for the wavy fin show an increase from 55% to 70% compared to plane fin. However, the friction factor is even greater, ranging from 66% to 140%.

Wang et al., 1999-e stated that heat transfer characteristics are strongly related to the corrugation angle (θ), with the waffle height (P_d) and the wavy length (P_o).

(Rich, 1975) indicated in his experimental data that the Colburn j factors are almost independent of the fin pitch to the Reynolds number calculated in the longitudinal tube pitch (P_l).

Wang et al., 2011 observed on their various investigations that the herringbone type wavy fin when compared with plane fin produces a significant increase of pressure loss for fin spacing lower than 1.6 mm, they also observed an increase in heat transfer of 5% to 10% for a corrugation angle lower than 20°.

Elshafei et al., 2010 investigated experimentally the heat transfer and pressure loss characteristics in wavy channels of parallel plates and made the following statements: The heat transfer and pressure loss average coefficients increased respectively by a factor of 2.6 to 3.2 and 1.9 to 2.6 for wavy channels of parallel plates. At the same time, the authors observed that the friction factor increases with increased channels spacing.

Kim and Youn (2013) stated that a heat exchanger compound of a wavy fin with waffle height of 2.79 mm has a heat transfer coefficient 4% higher and a pressure loss 10% higher compared to a heat exchanger compound of a wavy fin with waffle height of 2.39 mm.

Wang et al., 1997 made the following statements to a staggered tube arrangement: For $Re_{Dc}>900$ and $N_f>1$, the Colburn j factor increases slightly with decreasing of number of tube rows and the friction factor practically does not vary with the number of tube rows. For $Re_{Dc}<900$, they observed that both the friction factor is lower as the Colburn j factor is higher for the heat exchanger with the lowest number of tube rows.

2.3 Louver Fin Surface

Louver fin is widely used in residential air conditioning systems. It has the ability to break and restore air flow boundary layer, providing average heat transfer coefficients larger and better heat transfer is expected, in relation to the plane fin.

Wang et al., 2001 observed that the pressure loss always increases with increasing window angle and the heat transfer and friction increase with window length. At the same time, the authors stated that for a fixed window length (6.25 mm) and window angle (14°), there is a 10% reduction in heat transfer and a decrease of 41% of the pressure loss.

Tseng et al., 2015 tested eighteen heat exchangers, six of which were plane fins, six were louver fins and six were semi-dimple-type vortex generators, varying the fin pitch between 1.6 mm and 2.0 mm and the number of tube rows between 1, 2 and 4. The authors observed that louver fins showed higher convection heat transfer coefficients in relation to other, however also showed a greater pressure loss, and that the increase in the pressure loss was rather less than the increase in the heat transfer coefficient.

Pauley and Hodgson (1994) propose that the maximum angle is related to parameter $P_a/4H_j$. Note that H_j is the window height and P_a is the fin pitch.

Wang et al., 1998-b stated that the Colburn j factors decrease with the increase in the number of tube rows to $Re_{Dc}<2000$, and are relatively independent of the number of tube rows for $Re_{Dc}>2000$ e $N_f>1$. The friction coefficients vary slightly with the number of tube rows. The experimental data show that the Coburn j factor decreases with decreasing fin pitch to $Re_{Dc}<1000$. The authors also observed that the effect of fin pitch on the friction coefficient is very small compared with the plane fin configuration.

Čarija et al., 2014 performed an analysis of the heat transfer and pressure loss in heat exchangers with plane fin and louver fin. The authors observed that the heat transfer increases almost linearly with the increase in the window length. The convection heat transfer on average significantly increases with the increase of window angle until about 15°. After analyzing two heat exchangers both with 15° of window angle and 6 mm of window length, but a with 4 windows on the surface and the other with 5 windows on the surface, the authors observed that the exchanger that had the largest number of windows had an increase of 2.5% on the heat transfer. After analyzing two heat exchangers both a window length of 6 mm and with 5 windows on the surface, but a heat exchanger containing 15° of window angle, and the other containing 25° of window angle, the authors observed that the exchanger with greater window angle had a slight improvement in heat transfer.

2.4 Convex-Louver Fin Surface

The convex-louver surfaces are a combination between wavy and louver surfaces. In this type of intensification surface effects produced by waves overlap with the effects generated by windows, creating a complex flow configuration.

Wang et al., 1998-a, after comparing some convex-louver surfaces with some wavy surfaces equivalent, obtained values of increased between 21% and 48 %. According to the analysis carried out by (Zoghbi Filho, 2004) of the works of Wang and collaborators that evaluated the effects of the heat exchanger geometry together with the effects of convex-louver surfaces, the authors verified that the thermal-hydraulic performance for this surface depends on the fin pitch, mainly for heat exchangers with more than one row.

Wang et al., 2011 state that heat transfer characteristics are significantly better about wavy fins due to periodic renewal of thermal boundary layer. The authors also noted that the convex-louver fin is structurally more rigid when compared with a conventional louver fin.

Wang et al., 2011 show that the Colburn j factors for a convex-louver fin are 99% to 183% higher compared to plane fin and 21% to 48% higher compared to wavy fin.

2.5 Slit Fin Surface

The slit fins promote the development and the subsequent destruction of the boundary layer over the slits.

Wang et al., 1999-f investigated twelve heat exchangers and concluded that: for heat exchangers with two or more rows, the heat transfer coefficients of the slit fins were 78% to 150% higher than those of the equivalent plane fin. The authors observed that for fin pitch, air speed in the face and number of tube rows smaller intensifies the heat transfer.

Dejong and Jacobi (1997) indicated that this type of configuration promotes the appearance of vortex wakes for a certain Reynolds critical value, where such secondary flows improve heat transfer and pressure loss. The authors found that for fin pitch (P_a = 6.4 mm) results in high heat transfer coefficients and pressure loss.

(Yanagihara, 1996) stated that the heat transfer in the slit fins is affected by the plates thickness or slits and by the longitudinal and transverse distance between the interrupted surfaces.

Yun and Lee (1999) investigated rigorously eighteen exchangers with slit surfaces found that the fin pitch, slit angle, slit width and the slit height are the parameters that affect the thermal-hydraulic performance, where each one contributes respectively with 39%, 28%, 20% and 9%.

Jiong et al., 2011 analyzed a heat exchanger with slit fin composed of longitudinal vortex generators and stated that in relation to a heat exchanger with traditional slit fin promoted a better heat exchange with a slight increase in pressure loss.

2.6 Heat Exchanger with Vortex Generator

Fin-and-tube heat exchanger compound of vortex generators is another approach whose objective is increase the thermal-hydraulic performance of the exchanger. One of the ways to increase this performance is to improve the relationship between the Colburn j factor and the Fanning friction factor. Thus, to improve the thermal-hydraulic performance the vortex generators intensify the convection heat transfer rate in the exchanger producing a moderate pressure loss. Consequently, this can result in a smaller size exchanger design, lighter and cheaper.

Zeng et al., 2010 made the following comments on certain parameters which affect the thermal-hydraulic performance of a delta winglet type vortex generator: the higher the attack angle the greater the heat transfer and the pressure loss, being that between the angles of 30°, 45° and 60° which provides the best value for j/f is 45°. The higher the length and the height of the vortex generator the larger is the heat transfer and pressure loss, being that the length of 4 mm and height of 1.7 mm provide the best j/f. Both the convection heat transfer coefficient and the pressure loss decrease with the increase of the fin pitch and tube pitch.

3. COMPARISON BETWEEN PLANE, WAVY, LOUVER, CONVEX-LOUVER FINS AND VORTEX GENERATOR

This study was conducted using the correlations more suitable for each type of intensification surface under study. These correlations are described in (Zoghbi Filho, 2004) and considering the heat exchangers with fin collar outside diameters greater than 10.0 mm. In this analysis, the geometrical characteristics of the heat exchangers were maintained as close as possible.

For plane fin was considered the Wang et al., 2000-c correlation, for wavy fin was considered the Wang et al., 1999-c correlation, for louver fin was considered the Wang et al., 1999-a correlation, for convex-louver fin was considered the Wang et al., 1998-a correlation, for the slit fin was considered the Wang et al., 2001 correlation and for the semi-dimple type vortex generator was considered the Wang et al., 2014 correlation.

To define clearly which of the six intensification surfaces has the best thermal-hydraulic performance, the authors also plotted the Colburn j factor values and the Fanning friction factor values for each surface. The Figures 1 e 2 were built by (Zoghbi Filho, 2004), but the authors of this article included in this figure the vortex generator for comparison. After analyzing the Fig. 1, the authors of this article noted that the louver fin presented the greatest value of Colburn j factor and the second largest friction factor.

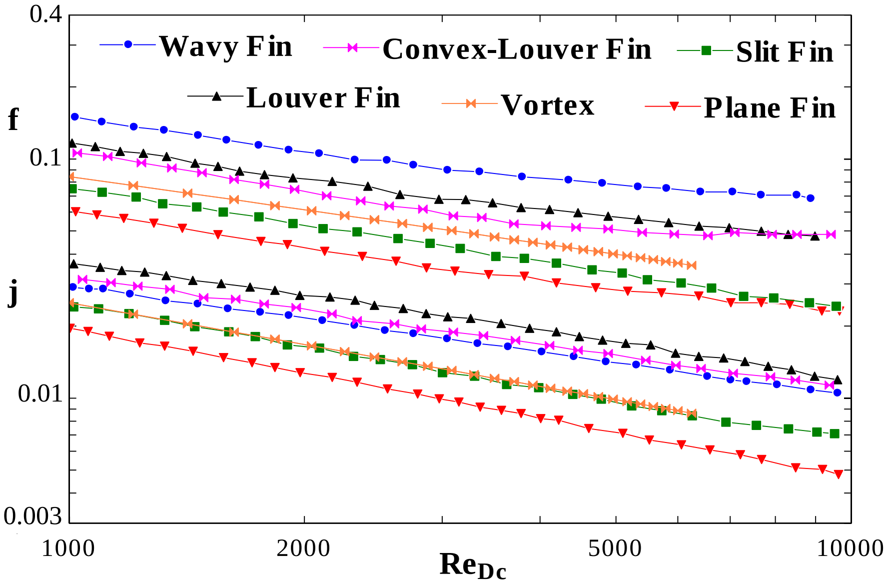

Figure 1. Heat transfer and pressure loss data obtained of plane, wave, louver, slit, convex-louver fins correlations and vortex generator correlation.

Thus, it was possible to evaluate the ratio (j/f) called area goodness factor, shown in Fig. 2. This parameter represents the heat transfer rate per frontal unit area and the surface with the greater value of (j/f) factor will require a smaller frontal area. Thus, for Re_{Dc}<6000 louver fin has the largest thermal-hydraulic performance, but when the Reynolds number increases the slit fin thermal-hydraulic performance increases until that for Re_{Dc}>6400 its performance overcome the louver fin thermal-hydraulic performance.

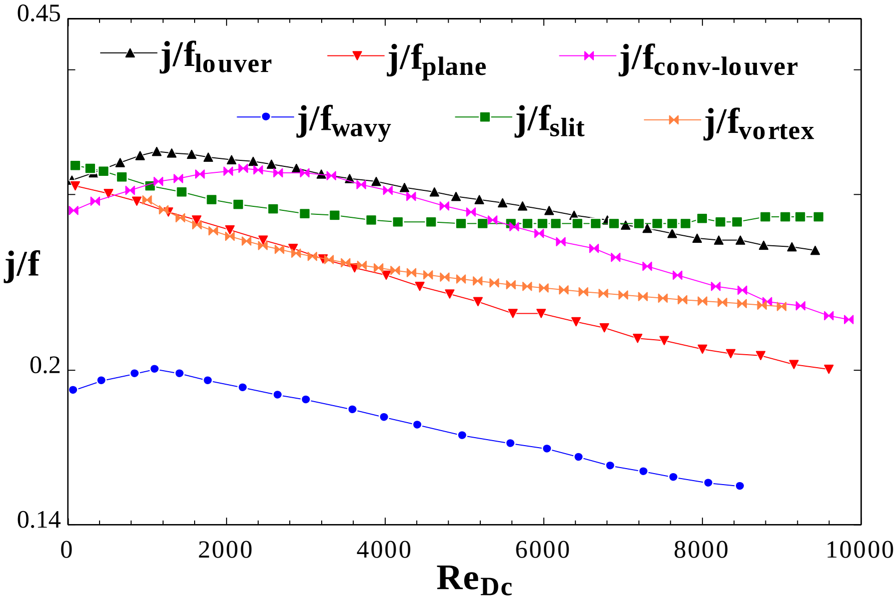

Figure 2. Values of j/f factor obtained of plane, wavy, louver, slit, convex-louver fins correlations and vortex generator correlation.

At the same time, the authors evaluated the thermal-hydraulic performance through of volume goodness factor for each surface and the result is shown in Fig. 3. Where this factor is given by the following expression $Z = \left[St/f^{1/3}\right]$ and represents the heat transfer rate and pumping power per unit area. This parameter tells that the surface with the greater value of Z factor will require a smaller volume for the same performance in terms of heat transfer as pumping power. Analyzing Figure 3, it was observed that the heat exchanger compound of a louver surface has the higher volumetric efficiency.

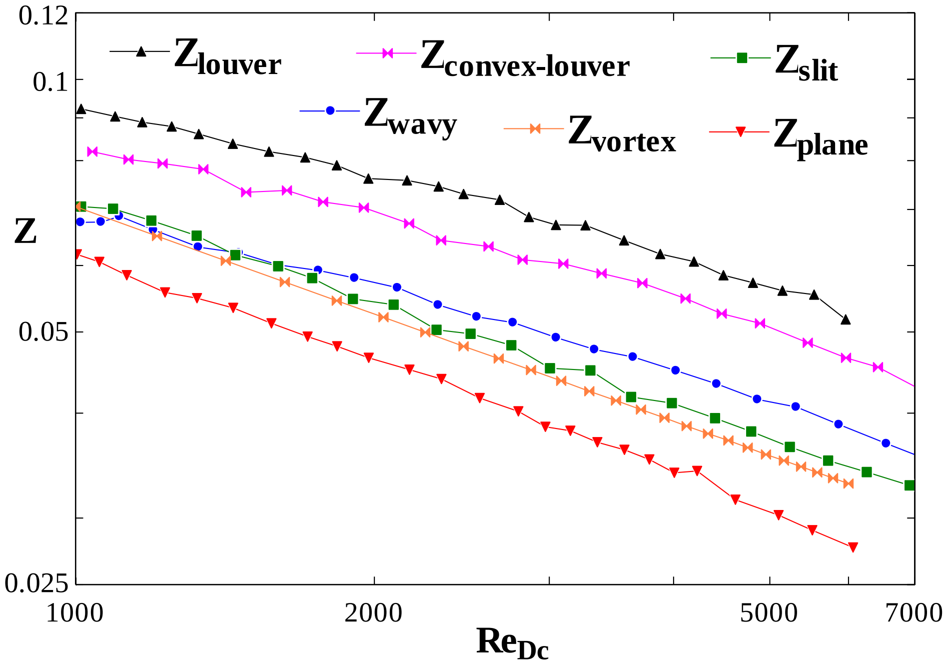

Figure 3. Values of Z factor in function of the Reynolds number.

4. COMPARISON BETWEEN THE EXPERIMENTAL RESULTS AND LITERATURE CORRELATIONS

(Pereira, 2012) tested the pressure loss over a fin-and-tube heat exchanger compound of a wavy surface with tube outer diameter higher than 13 mm in CEFET-MG refrigeration laboratory. By means of this experiment, (Pereira, 2012) calculated the Fanning friction factor for each of the measured experimental data. At last, it was realized a comparison between the experimental results obtained and two correlations that can be used in the heat exchanger under study, as shown in Fig.4.

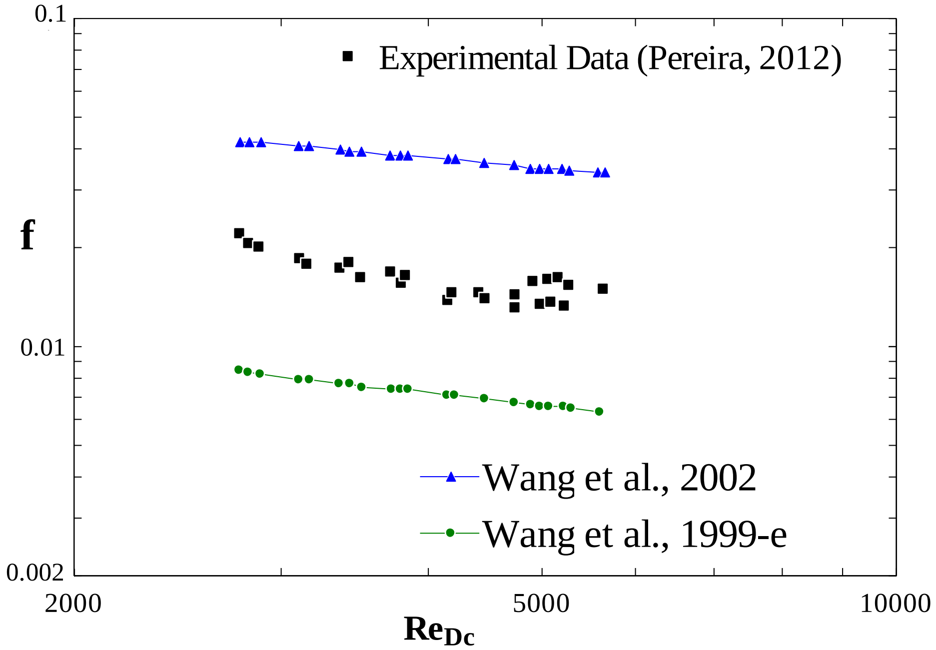

Figure 4. Comparison between the experimental friction factor and the Wang et al., 1999-e and Wang et al., 2002 correlations in function of the Reynolds number.

The Wang et al., 1999-e correlation presented a friction factor in average 55% lower than that obtained experimentally, whereas the Wang et al., 2002 correlation presented a friction factor in average 135% greater than that obtained experimentally. Such behavior may be associated with the sensitivity of the correlations with the geometrical parameters of the heat exchanger because the geometrical parameters tested were obtained by direct measurement equipment.

(Zoghbi Filho, 2004) also tested the pressure loss and the heat transfer rate over a fin-and-tube heat exchanger compound of a wavy surface with geometrical characteristics similar to heat exchanger tested by (Pereira, 2012). His experimental results were compared with the Kim et al., 1997 and Wang et al., 1999-c correlations, as shown in Fig.5.

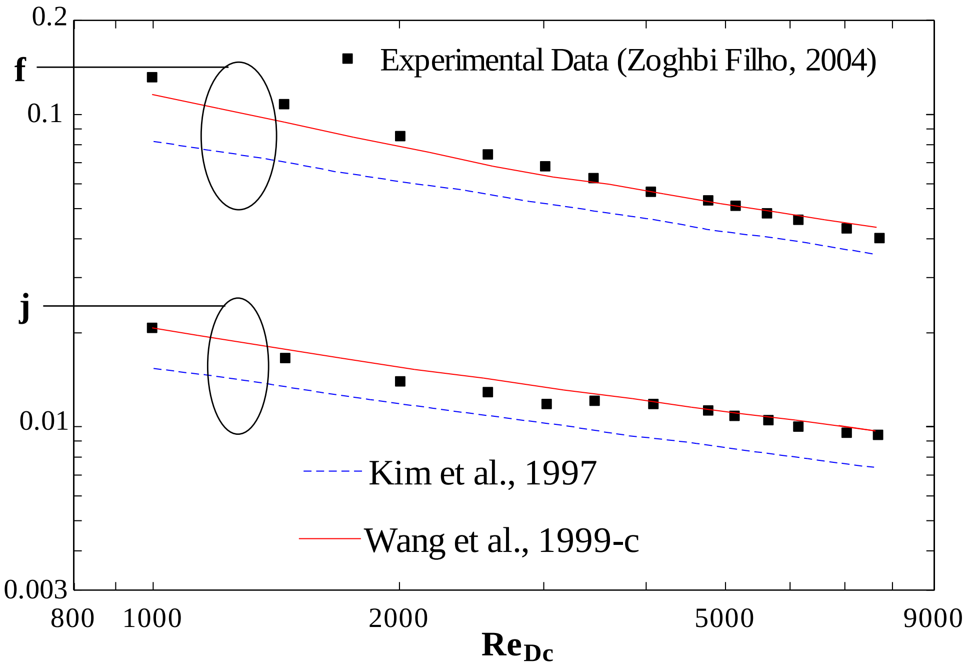

Figure 5. Comparison between the Kim et al., 1997 and Wang et al., 1999-c correlations with experimental results obtained in function of the Reynolds number.

The Kim et al., 1997 correlation presented lower values for the j e f factors compared with experimental results. This is connected with differences in the geometrical aspects of the heat exchangers. The Wang et al., 1999-c correlation agrees very well with the experimental results, because of the similar geometrical characteristics both of the heat exchanger compound of wavy surface under study as database by which the correlation was generated.

The table 1 was built by the authors of this article, it presents the correlations used in this topic.

Table 1. Correlations for wavy fin used in this topic.

Wavy Fin: Wang et al., 1999-c	
$j = 0.324 \cdot Re_{Dc}^{J_1} NN^{J_2} (\tan\theta)^{J_3} (B)^{-J_4} \cdot N_f^{0.428}$ Where: $J_1 = -0.229 + 0.115(C)^{0.6}(K)^{0.54} N_f^{-0.284} \cdot \ln(0.5 \cdot \tan\theta)$ $J_2 = -0.251 + \frac{0.232 \cdot N_f^{1.37}}{(\ln(Re_{Dc}) - 2.303)}$ $J_3 = -0.439(O)^{0.09}(B)^{1.75} N_f^{-0.93}$ $J_4 = 0.502(\ln(Re_{Dc}) - 2.54)$ Where: $\boxed{NN = (P_a / E_{ea})}$, $\boxed{B = (E_t / E_l)}$, $\boxed{K = (E_l / D_h)}$	$f = 0.01915 \cdot Re_{Dc}^{F_1} (\tan\theta)^{F_2} (N)^{F_3} \cdot \left(\ln\left(\frac{A_{total}}{A_{pri}}\right)\right)^{-5.35} (P)^{1.3796} N_f^{-0.0916}$ Where: $F_1 = 0.4604 - 0.01336(N)^{0.58} \cdot \ln\left(\frac{A_{total}}{A_{pri}}\right)(\tan\theta)^{-1.5}$ $F_2 = 3.247(N)^{1.4} \cdot \ln\left(\frac{A_{total}}{A_{pri}}\right)$ $F_3 = \frac{-20.113}{\ln(Re_{Dc})}$ $\boxed{O = (P_a / D_h)}$, $\boxed{P = (D_h / D_c)}$, $\boxed{N = (P_a / E_l)}$, $\boxed{C = (P_a / D_c)}$
Wavy Fin: Wang et al., 1999-e	

$$j = 1.79097 \cdot Re_{Dc}^{-0.1707-1.374\cdot(E_l/E_a)^{-0.493}(P_a/D_c)^{-0.886}}\ N_f^{-0.143}\left(P_d/P_o\right)^{-0.0296}\left(\frac{E_l}{E_a}\right)^{-0.456} N_f^{-0.27}\left(\frac{P_a}{D_c}\right)^{-1.343}\left(\frac{P_d}{P_o}\right)^{0.317}$$

$$f = 0.05273 \cdot Re_{Dc}^{f_1}\left(\frac{P_d}{P_o}\right)^{f_2}\left(\frac{P_a}{E_t}\right)^{f_3}\left[\ln\left(\frac{A_{total}}{A_{pri}}\right)\right]^{-2.726}\left(\frac{D_h}{D_c}\right)^{0.1325} N_f^{0.02305}$$

$$f_1 = 0.1714 - 0.07372\left(\frac{P_a}{E_l}\right)^{0.25}\ln\left(\frac{A_{total}}{A_{pri}}\right)\left(\frac{P_d}{P_o}\right)^{-0.2} \qquad f_2 = 0.426\left(\frac{P_a}{E_t}\right)^{0.3}\ln\left(\frac{A_{total}}{A_{pri}}\right) \qquad f_3 = \frac{-10.2192}{\ln\left(Re_{D_c}\right)} \qquad \boxed{D_h = \frac{4\cdot A_c \cdot L}{A_{total}}}$$

Wavy Fin: Kim et al., 1997

For $N_f \geq 3$:

$$j_3 = 0.394 \cdot Re_{Dc}^{-0.357} B^{-0.272} T^{-0.205} X^{-0.558} Y^{-0.133}$$

$$f_a = 4.467 \cdot Re_{Dc}^{-0.423} B^{-1.08} T^{-1.08} X^{-0.672} \cdot \left(A_{sec}/A_{total}\right)$$

Where:

$\boxed{B = (E_t / E_l)}$, $\boxed{T = (E_{ea} / D_c)}$, $\boxed{X = (P_o / P_d)}$, $\boxed{Y = (P_d / E_{ea})}$

Wavy Fin: Wang et al., 2002

$$f = 0.228 \times Re_{Dc}^{f1}\left(tg\theta\right)^{f2}\left(\frac{E_{ea}}{E_l}\right)^{f3}\left(\frac{E_l}{D_C}\right)^{f4}\left(\frac{D_C}{D_h}\right)^{0.383}\left(\frac{E_l}{E_t}\right)^{-0.247}$$

Where:

$$f1 = -0.141\left(\frac{E_{ea}}{E_l}\right)^{0.0512}\left(\tan\theta\right)^{-0.472}\left(\frac{E_l}{E_t}\right)^{0.35}\left(\frac{E_l}{D_h}\right)^{0.449\cdot\tan\theta} N_f^{-0.049+0.23\tan\theta}$$

$$f2 = -0.562\left(\ln(Re_{Dc})\right)^{-0.0923} N_f^{0.013}, \quad f3 = 0.302 \cdot Re_{Dc}^{0.03}\left(\frac{E_t}{D_c}\right)^{0.026}$$

$$f4 = -0.306 + 3.63\tan\theta$$

$$j = 0.0646 \cdot Re_{Dc}^{j_1} \cdot \left(\frac{D_c}{D_h}\right)^{j_2}\left(\frac{E_{ea}}{E_t}\right)^{-1.03}\left(\frac{E_l}{D_c}\right)^{0.432}\left(\tan\theta\right)^{-0.692} N_f^{-0.737}$$

$$j_1 = -0.0545 - 0.0538\tan\theta - 0.302 \cdot N_f^{-0.24} \cdot \left(\frac{E_{ea}}{E_l}\right)^{-1.3}\left(\frac{E_l}{E_t}\right)^{0.379}\left(\frac{E_l}{D_h}\right)^{-1.35}\tan\theta^{-0.256}$$

$$j_2 = -1.29\left(\frac{E_l}{E_t}\right)^{1.77-9.43\tan\theta}\left(\frac{D_c}{D_h}\right)^{0.229-1.43\tan\theta} \cdot N_f^{-0.166-1.08\tan\theta}\left(\frac{E_{ea}}{E_t}\right)^{-0.174\ln\left(0.5N_f\right)}$$

5. CONCLUSIONS

In this study, six types of fin-and-tube heat exchangers were compared using empirical correlations available in the literature for the calculation of heat transfer (Colburn j factor) and the pressure loss (friction factor), where the main characteristic evaluated was the kind of intensification surface adopted. Therefore, after analyzing the results of this study, it was concluded that the fin-and-tube heat exchanger compound of louver fin presented the higher heat transfer coefficient and the second largest pressure of loss, although the louver fin obtained greater superficial and volumetric heat transfer efficiency. Therefore, it was concluded that, in fact, louver fin obtained the largest thermal-hydraulic performance in relation to other surfaces.

After analyzing the graphics produced by (Pereira, 2012) and (Zoghbi Filho, 2004), where they compared their experimental results with correlations which can be applied to a fin-and-tube heat exchanger compound of a wavy surface, the authors of this article concluded that although more than one correlation can be applied to a particular type of heat exchanger, not all correlation will provide with good accuracy values of friction factor and of Colburn j factor concerning this equipment. Therefore, the most suitable correlation for the heat exchanger compound of a wavy surface is a correlation which has the geometrical characteristics closest to the heat exchanger under study.

The result obtained in this article corresponds to a first analysis regarding the theme proposed. Thus, as a suggestion for future works would be interesting to perform a larger number of experimental investigations to obtain a result increasingly reliable and trustworthy.

6. REFERENCES

Čarija, Zoran et al., 2014. “Heat transfer analysis of fin-and-tube heat exchangers with flat and louvered fin geometries”. *International journal of refrigeration*, Vol. 45, p. 160-167.

Chen, Z. Q.; Ren, J. X., 1988. “Effect of fin spacing on the heat transfer and pressure drop of a two-row plate fin and tube heat exchanger”. *International journal of refrigeration*, Vol. 11, n. 6, p. 356-360.

Dejong, N. C.; Jacobi, A. M., 1997. “An experimental study of flow and heat transfer in parallel-plate arrays: local, row-by-row and surface average behavior”. *International Journal of Heat and Mass Transfer*, Vol. 40, n. 6, p. 1365-1378.

Elshafei, E. A. M. et al., 2010. "Heat transfer and pressure drop in corrugated channels". *Energy*, Vol. 35, n. 1, p. 101-110.

Gray, D. L.; Webb, R. L., 1986. "Heat transfer and friction correlations for plate finned-tube heat exchangers having plain fins". *In: Proceedings of the 8th International Heat Transfer Conference*, p. 2745-2750.

Kim, N. H., Yun, J. H., WEBB, R. L., 1997. "Heat Transfer and Friction Correlations for Wavy Plate Fin and-Tube Heat Exchangers". *Journal of Heat Transfer*, vol. 119, p. 560-567.

Kim, N. H.; Youn, B., 2013. "Airside Performance of Fin-and-Tube Heat Exchangers having Sine Wave or Sine Wave-Slit Fins". *Journal of Enhanced Heat Transfer*, Vol. 20, n. 1.

Li, Jiong et al., 2011. "Numerical study on a slit fin-and-tube heat exchanger with longitudinal vortex generators". *International Journal of Heat and Mass Transfer*, Vol. 54, n. 9, p. 1743-1751.

Pauley, Laura L.; Hodgson, Judith E., 1994. "Flow visualization of convex louver fin arrays to determine maximum heat transfer conditions". *Experimental thermal and fluid science*, Vol. 9, n. 1, p. 53-60.

Pereira, L. C. O., 2012. *Análise experimental de um trocador de calor do tipo serpentina aletada para utilização em sistemas térmicos*. Dissertação (mestrado). Centro Federal de Educação Tecnológica de Minas Gerais, Belo Horizonte.

Rich, D. G., 1975. "The effect of the number of tube rows on heat transfer performance of smooth plate fin-and-tube heat exchangers". ASHRAE Trans, Vol. 81, n. 1, p. 307-317.

Seshimo, Yu; Fujii, M., 1991. "An experimental study on the performance of plate fin and tube heat exchangers at low Reynolds numbers". *In: Proceedings of the 1991 ASME JSME thermal engineering joint conference*.

Tseng, C. Yung et al., 2015. "An experimental study of the air-side performance of fin-and-tube heat exchangers having plain, louver, and semi-dimple vortex generator configuration". *International Journal of Heat and Mass Transfer*, Vol. 80, p. 281-287.

Wang, C. C. et al., 1996. "Sensible heat and friction characteristics of plate fin-and-tube heat exchangers having plane fins". *International Journal of Refrigeration*, Vol. 19, n. 4, p. 223-230.

Wang, C. C.; Fu, W. L.; Chang, C. T., 1997. "Heat transfer and friction characteristics of typical wavy fin-and-tube heat exchangers". *Experimental thermal and fluid science*, Vol. 14, n. 2, p. 174-186.

Wang, C. C.; Tsai, Y. M.; Lu, D. C., 1998-a. "Comprehensive study of convex-louver and wavy fin-and-tube heat exchangers". *Journal of thermophysics and heat transfer*, Vol. 12, n. 3, p. 423-430.

Wang, C.C. et al., 1998-b. "An experimental study of heat transfer and friction characteristics of typical louver fin-and-tube heat exchangers". *International journal of heat and mass transfer*, Vol. 41, n. 4, p. 817-822.

Wang, C.C. et al., 1999-a. "Heat transfer and friction correlation for compact louvered fin-and-tube heat exchangers". *International journal of heat and mass transfer*, Vol. 42, n. 11, p. 1945-1956.

Wang, C. C.; Jang, J.Y.; Chiou, N.F., 1999-c. "Technical Note A heat transfer and friction correlation for wavy fin-and-tube heat exchangers". *International Journal of Heat and mass transfer*, Vol. 42, n. 10, p. 1919-1924.

Wang, C.C. et al., 1999-e. "Investigation of wavy fin-and-tube heat exchangers: a contribution to databank". *Experimental Heat Transfer*, Vol. 12, n. 1, p. 73-89.

Wang, C.C.; Tao, W.H; Chang, C.J., 1999-f. "An investigation of the airside performance of the slit fin-and-tube heat exchangers". *International Journal of Refrigeration*, Vol. 22, n. 8, p. 595-603.

Wang, C.C.; Chi, K.Y; Chang, C.J., 2000-c. "Heat transfer and friction characteristics of plain fin-and-tube heat exchangers, part II: Correlation". *International Journal of Heat and Mass Transfer*, Vol. 43, n. 15, p. 2693-2700.

Wang, C.C.; Lee, W.S.; Sheu, W.J., 2001. "A comparative study of compact enhanced fin-and-tube heat exchangers". *International Journal of Heat and Mass Transfer*, Vol. 44, n. 18, p. 3565-3573.

Wang, C.C.; Hwang, Y,M; Lin, Y.T., 2002: "Empirical correlations for heat transfer and flow friction characteristics of herringbone wavy fin-and-tube heat exchangers". *International Journal of Refrigeration*, Vol. 25, n. 5, p. 673-680.

Wang, C. C., 2011. "Recent advances in fin-and-tube heat exchanger". *International Journal of Air-Conditioning and Refrigeration*, Vol. 19, n. 04, p. 291-301.

Wang, C. C.; Chen, K.; Lin, Y. T., 2014. " Investigation of the semi-dimple vortex generator applicable to fin-and-tube heat exchangers". *Applied Thermal Engineering*.

Yanagihara, J. I., 1996. *Intensificação de Transferência de Calor: Geradores de Vórtices Aplicados a Trocadores de Calor Tubo-Aleta Compactos*. Tese de Livre Docência, Escola Politécnica da Universidade de São Paulo.

Yun, J.Y.; Lee, K. S., 1999. "Investigation of heat transfer characteristics on various kinds of fin-and-tube heat exchangers with interrupted surfaces". *International Journal of Heat and Mass Transfer*, Vol. 42, n. 13, p. 2375-2385.

Zeng, M., et al., 2010. "Optimization of heat exchangers with vortex-generator fin by Taguchi method". *Applied Thermal Engineering*, Vol. 30, n.13, p. 1775-1783.

Zoghbi Filho, J. R. B., 2004. *Avaliação teórico/experimental do desempenho termo-hidráulico do ar em trocadores de calor tipo serpentina*. Tese (doutorado). Universidade de São Paulo, Escola de Engenharia de São Carlos, São Carlos.

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