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EXPERIMENTAL DATA COMPARISON AND PREDICTION OF A PLAIN FIN-AND-TUBE HEAT EXCHANGER

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Abstract. *This work investigated a plain fin-and-tube heat exchanger in a closed-loop wind tunnel. Hot water was forced into the tubes and it was refrigerated by forced air flowing over the fins. Water flow rate was fixed at 3.5* l/min*, air velocity ranged from 1.4 to 2* m/s*, and outer surface area was 1.0264* m*. Experimental results were reduced with* $\epsilon - NUT$ *approach and Colburn factor was calculated. Literature correlations were confronted with measured data in order to verify performance and applicability. An additional data-base with 57 distinct heat exchangers from literature was added to our data and a new correlation for Colburn factor was developed. The mean absolute error were calculated for each correlation and the new one presented the lowest error, 12.4%*
Keywords: *plain fin-and-tube, heat exchanger, Colburn factor*

1. INTRODUCTION

Heat can be defined as energy transferred between bodies of different temperatures. Several applications use the heat transfer mechanism to support, monitor and initiate processes in the industry. Heat exchangers are an indispensable item for the development and maintenance of the refrigeration industry (Wang *et al.* (1996) and Pirompugd *et al.* (2006)). Increasing the performance of heat exchangers is desirable since it directly impacts the costs in material, energy efficiency and others.

Heat exchangers have several configurations, one of the simplest being plain fin-and-tube. These types of heat exchangers are commonly used in the refrigeration and air-conditioning industry due to their low cost, uncomplicated manufacturability and with a large experimental database, when compared to other geometries. These heat exchangers are usually made of aluminium, and may have copper or aluminium tubes (Wang and Chi (1998a)).

Even so, it has been reported that the methods of prediction of heat transfer in varied fin exchangers is insufficient, especially methods that evaluate different ranges of geometries (Qasem and Zubair (2018)). Therefore, this work will present a bibliographic review on heat exchangers for the air side. The method used to reduce the experimental data will be described. Finally, experimental data will be presented and compared.

2. REVIEW

Heat exchangers development has a direct impact on refrigeration industry. In order to facilitate the project and construction, correlations were proposed which can predict the heat transfer behaviour of a heat exchanger project for a set of geometrical parameters. If those correlation have enough precision, it will be possible to test different project with ease before spending time and resources in numerous experimental tests. The Tab. 1 summarize geometrical and viscous parameters from works of many authors along the years.

One of the pioneers in this study was Gray and Webb (1986) which applied a multiple regression technique to non-dimensional parameters for Colburn factor prediction equation. By trial and error they used Root Mean Square (RMS) error in order to verify equation's performance. The author gather different experimental data from various sources and reported building firstly a correlation for an N equal to four and a second equation to adjust lower N numbers. Their conclusion point to an independence of Colburn factor for a $N \geq 4$.

Later, Kayansayan (1992) used a different approach to developed his correlation. His work investigated 10 distinct heat exchanger inside a wind tunnel in open-loop configuration with a controlled velocity of 0 - 15 m/s and a fixed water temperature of $85°C$. Overall Heat Transfer Coefficient method (U), alongside with Logarithmic Mean Temperature Difference (LMTD), was used to reduce data for outside heat transfer coefficient and Colburn factor. The experiments resulted on a refined data of 110 points, applying a least square curve fit the author suggested a straightforward correlation for Colburn factor with only two parameters. Analysis showed that Colburn factor is strongly dependent on a relation between total outside area and tube outside area. Fin density is a main factor, as for a higher fin density leads to a higher outside area and, in consequence, a lower Colburn factor.

A few years later, Wang *et al.* (1996) gathered new data for plain fin plate heat exchangers. The idea for their work was to include data for a gap in geometry from tube diameter in the literature. Their data include heat exchanger with same Dc, P_t, and P_l for different fin spacing and row number. This experiment was also conducted in an open-loop mode wind tunnel with air velocities varying from 0.3 - 6.2 m/s and a fixed water temperature of $60°C$. Different from Kayansayan (1992), reduction data was achieved with $e - NUT$ method for both unmixed fluids in cross-flow configuration. With Gnielinski correlation for prediction of inside tube heat transfer coefficient (h_i) and NTU calculation for U value, the external heat transfer coefficient was calculated. For correlation development, a multilinear reduction method was applied for a range o experimental data. It was reported that for a low Re, the higher Colburn factor was archived at larger number of rows and smaller fin spacing somewhat contradicting Gray and Webb (1986) conclusion ($N > 4$). Also, reported that fin spacing is negligible in Colburn factor. Next year, Wang *et al.* (1997) tested for the first time dehumidifying condition in heat exchangers with plain fin for air side. Wang's work justified that those kind of work are rare. This time, the authors used a closed-loop wind tunnel with different humidity level and water temperature lower than air temperature. 6 different fin-and-tube heat exchanger were tested, where they aimed to see the influence of fin density and number of rows in heat exchange efficiency under fully dry and fully wet condition. Heat transfer coefficient was reported being reduced by Threlkeld method, which is based in the mean entalpy difference, U and heat transfer resistance method. The correction factor were used for unmixed/unmixed configuration. Gnielinski and a constant for thickness of water film were adopted. They have used the same method to reduce their experimental data to propose two new correlation for Colburn factor where, $j = fn(Re, N, e)$. The Same finning factor (e) as Kayansayan (1992), was used. This work concluded that Colburn factor for sensible heat is not dependent on the inlet air conditions. Wang and Chi (1998a) returned to sensible only heat verification. This work was also divided in two part. Wang and Chi (1998a) present new set of experimental data for plain fin-and-tube heat exchanger with a smaller diameter of tube (9.52 mm), which is reported to be lacking in the literature. An approach similar to previous work was used. Eighteen different heat exchanger were tested (eleven had D_c smaller than 10.23 mm) in and open-loop wind tunnel, with the same configuration as Wang *et al.* (1997). Data reduction adopted $e - NTU$ and thermal resistance method, where 5 set of correlation, a different correlation for $N = 1, 2, 3, 4$ and ∞, were adopted to estimate NTU in cross-flow for and unmixed-unmixed configuration. The effect on Colburn factor was said to be negligible for $N \geq 4$ and $Re_{D_c} > 2000$ due to vortex formation along the fin and N effect is pronounced at low Re number when N and fin density are large. This result confront Kayansayan (1992) statement, once again when reports that heat transfer coefficient increase with smaller fin density for a low Re and N number. Also, a contradiction can be pointed to Wang *et al.* (1996) conclusion about fin density effects on Colburn factor. Wang and Chi (1998b) continues the previous analysis using their and other authors data to build a data-base, in an approach similar to Gray and Webb (1986). New correlations based on a wider data-base are exalted, in order to improve performance. Wang and Chi (1998b) use a total of 74 different samples from 8 different authors with a total of 676 points to build this data-bank. A multiple linear regression method is applied and the equation proposed are then compared with 3 authors correlations. Wang and Chi (1998b) reported that 88.6% of the data-bank was successful described with an 15% deviation.

Data-base and reduced data for correlation technique were being in high use, following same tendency for built a data-base Kim *et al.* (1999) did a review for experimental data regard plain fin-and-tube heat exchangers and correlation for Colburn factor. A multiple regression technique was applied and R-squared value was measured to verify accuracy of equations. Various non-dimensional values based on geometrical parameters were tested by trial and error and those with highest R-squared error were selected. Kim *et al.* (1999) was used as an extension for (Gray and Webb, 1986) correlation work with new data for small tube diameter. A total of 47 different heat exchangers were used with no mention to a total number of points. Their correlation reported to predict 94% of their data-base with 20% deviation.

Up to this point, only a few works covered moist-air related topic. Most works have addressed dry or fully wet condensation state in plain fin-and-tube heat exchangers. Pirompugd *et al.* (2006) tried to address this gap in the literature by using a different method of data reduction and proposing new sets of correlations. Their work used a closed-loop wind tunnel which covered relative humidity from 50 up to 90% for a good range of velocities (0.3 - 4.5 m/s). 18 distinct heat exchangers were tested with diverse geometries range. Two different reduction methods were applied for fully wet and fully dry condition, respectively. First method was based on Threlkeld's method using entalphy difference applied to small circular segments over the fins. A cross-flow configuration were adopted and , as (Kayansayan, 1992), Myers constant for water film was adopted. Using Gnielinski correlation for water heat transfer coefficient, thermal resistance method were applied to find external heat transfer coefficient. Modified Threlkeld's equation for wet fin efficiency was used to solve interactively the problem by checking the sum of all segment with the heat transfer rate. For fully dry fins, a logarithmic mean temperature method was applied with same small regions as previous method. A traditional approach was used with F factor adopted as unity. Thermal resistance with Gnielisnki correlation were also used and, again, the set of equation were solved for each segment which later were compared with total heat transfer rate. This work suggested 4 sets of Colburn factor correlation for dry, partially wet and totally wet condition using a multiple linear regression method for a data range set. Concluded that the applied method is superior to traditional ones and reported that inlet humidity does not have effect in prediction for the applied method. Heat transfer is said to be independent of fin density, justified by water condensate changing air flow patter causing better mixing characteristics and for $N \geq 4$, no impact could be associated, with heat transfer which comes to agreement with (Gray and Webb, 1986). Under same justification, Pirompugd *et al.* (2007) used their previous method for 36 different plain fin-and-tube heat exchangers using same methodology of previous work. They presented a set of 4 new correlation for, dry, partially wet and wet condition. It was found that inlet humidity does not affect heat transfer performance, which agree with previous work. On contrary to dry data, wet condition has independence of fin density due to air flow mixture increase as reported earlier, also, when $N \geq 4$ sensible heat transfer coefficient is about the same.

Recently, Kim (2015) investigated smaller tube diameters (7.3 mm) for plain fin-and-tube heat exchanger under dehumidifying condition. nine different heat exchangers, with micro-fin for tube side, were tested in an open-loop wind tunnel with inside temperature and relative humidity fixed at 32 $°C$ and 80%, respectively. Data were reduced with $e - NUT$ method and thermal resistance. Park correlation was used to predict tube side water heat transfer coefficient. Kim (2015) reported that fin density has no effect for Colburn factor in agreement with author above. Colburn factor was found to decrease as N increases, which agrees with Wang and Chi (1998a). Also, diameters of 5.3 mm presented higher Colburn factor if compared to 7.3 mm geometries.

Although there is a substantial number of correlations for the prediction of the Colburn factor, the equations are limited to a small range of geometries (Qasem and Zubair, 2018). Thus, this work aims to contribute with a new correlation that is easy to use and built under a diverse data-base in order to predict the Colburn factor in plain fin-and-tube heat exchangers.

Table 1: Geometric range study of authors

Author	D_c (mm)	P_t(mm)	P_l(mm)	S_p(mm)	t(mm)	N(-)	Re_{Dc}(-)
Gray and Webb (1986)	9.96 - 17.17*	1.82 - 2.60 **	1.70 - 2.79 **	0.17 - 0.64 **	0.011 - 0.032	-	1,000 - 21,000
Kayansayan (1992)	9.92 - 16.7	25.4 - 40	22 - 34.67	-	0.2	4	522 - 22,101
Wang *et al.* (1996)	10.23	25.4	22	1.57 - 3.03	0.13 - 0.2	2 - 6	350 - 7,600
Wang *et al.* (1997)	10.23	25.4	22	3.07	0.13	2 - 6	350 - 6,850
Wang and Chi (1998a)	7.53 - 10.23	21 - 25.4	12.7 - 19.05	1.105 - 2.20	0.115	1 - 4	275 - 7,650
Wang and Chi (1998b)***	6.59 - 13.64	17.7 - 31.75	12.4 - 27.5	1.095 - 3.66	0.115 - 0.2	1 - 6	260 - 19,000
Kim *et al.* (1999)***	7.30 - 19.51	20.32 - 50.80	17.58 - 43.99	0.990 - 8.55	0.110 - 0.406	1 - 8	480 - 24,500
Pirompugd *et al.* (2006)	8.51 - 10.34	25.4	19.1 - 22	1.075 - 3.03	0.115 - 0.130	1 - 6	300 - 5,000
Pirompugd *et al.* (2007)	8.51 - 10.34	17.7 - 25.4	1.27 - 2.20	1.075 - 3.03	0.115 - 0.130	1 - 6	300 - 5,000
Kim (2015)	5.3	19.5	11.2	0.98 - 1.18	0.12	1 - 3 t'	250 - 1,100

* Outside diameter.
** Normalized by D_c.
*** Does not add any new experimental data.

3. EXPERIMENTAL METHODOLOGY

The experiments were conducted in a Heat Transfer Research Group's laboratory at EESC-USP using a wind tunnel operating in close-loop mode. A plain fin-and-tube heat exchanger was installed inside the tunnel's test section where the air speed ranged from 1.4 to 2 m/s. Air speed was measured by a nozzle plate, while hot water was forced inside the heat exchanger in order to evaluate heat transfer rate. Water entrance temperature and water flow rate were fixed at 50$°C$ and 3.5 l/min, respectively. Type-T thermocouples were used to measure inlet and outlet of both air and water temperature. Air humidity was also acquired, ranging from 25% to 40%. Atmospheric pressure was measure as 92.9 kPa by the time of the experiments.

Fig. 1 shows the schematic for the experiment. The heat exchanger used is a plain fin-and-tube heat exchanger, made both fin and tubes of aluminium, and has a total heat transfer surface area of 1.026 m^2, where N is equal to 2, D_c to 10.1 mm, frontal area of 0.214 m x 0.200 m and F_p of 3.1 mm.

3.1 Data reduction

To estimate external flow Colburn factor, $\epsilon - NUT$ method was used. The equations are described bellow:
Firt step is to determine the heat transfer rate between water and air using energy analysis over the heat exchanger Eq. (1)

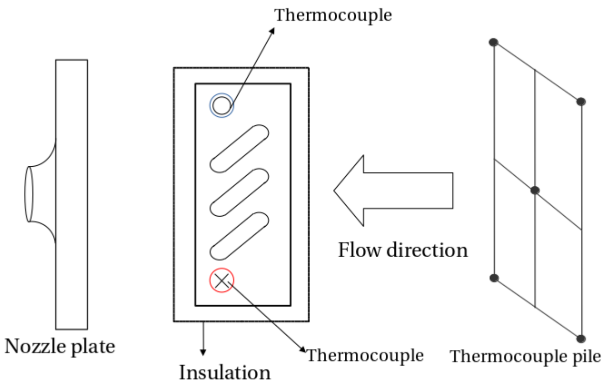
$$\overline{q} = \frac{q_{air} + q_{water}}{2} = \frac{|\dot{m}_{air}c_{p,air}\left(T_{air,in} - T_{air,out}\right)| + |\dot{m}_{water}c_{p,water}\left(T_{water,in} - T_{water,out}\right)|}{2} \tag{1}$$

where q_{air} and q_{water} are air and water heat transfer rate, respectively. Effectiveness (ϵ) can be then estimated by Eq. (2)

$$\epsilon = \frac{\overline{q}}{C_{min}\left(T_{water,in} - T_{air,in}\right)} \tag{2}$$

where C_{min} is the smaller heat capacity of both fluids. Next step, find the number of thermal units (NTU) for this specific heat exchanger. Kim (2015) used NTU as $f(\epsilon, C)$, where C is the rate between maximum and minimum heat capacity

Figure 1: Experiment diagram.



(Eq. (4)), for heat exchanger with air side with mixed fluid and water side unmixed, while Wang and Chi (1998b) and Wang *et al.* (1996) used equation for both unmixed fluids. In this work, an unmixed-mixed approach was adopted, Eq. (3), as both methods were previously applied with successful data reduction.

$$NTU = \frac{\ln\left(C\ln\left(1-\epsilon\right)+1\right)}{C} \tag{3}$$

$$C = \frac{C_{min}}{C_{max}} \tag{4}$$

Overall heat exchange coefficient can now be evaluated with Eq. (9) and heat exchange coefficient can be calculated by Eq. (6)

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

$$\frac{1}{UA_s} = \frac{1}{\eta A_s h_o} + R_{cond} + \frac{1}{A_i h_i} \tag{6}$$

where η is the fin efficiency for an adiabatic tip, which solved simultaneously among Eq. (7), Eq. (8), and Eq. (6), h_o outer heat transfer coefficient, R_{cond} thermal resistivity portion related to conduction which was neglected in this work as this value is way lesser than other 2 counterparts, A_i tube internal section area, and h_i water heat transfer coefficient which was estimated using Gnielinski correlation.

$$m = \frac{2h_o}{\sqrt{k_{mat}\delta}} \tag{7}$$

$$\eta = \frac{\tanh\left(mL_c\right)}{mL_c} \tag{8}$$

Where k_{mat} is the conductivity of the heat exchanger, δ fin hight, and $L_c = \delta + \frac{t}{2}$.

Finally, Nusselt number can be calculated with Eq. (9) and Colburn factor by Eq. (10)

$$Nu = \frac{h_o D_c}{k_{air}} \tag{9}$$

$$j = \frac{Nu}{RePr^{1/3}} \tag{10}$$

where k_{air} is the air conductivity, Pr the Prandtl number and Re the Reynolds number based on maximum air velocity. A correlation summary for Colburn factor used in this work can be seen in Tab. 2.

3.2 Literature data-base

In addition to the experiments performed a database was acquired from the available literature where papers with plain fins with experimental data were consulted. The geometric parameter were then organized in Tab. 3. A total of 58 distinct heat exchanger were used to built this data-base where, 57 are from data present in literature and 1 from experimental data. A sum of 361 points for Colburn factor was acquired. The data was acquired in tables and figures of referenced authors. In order to avoid error propagation, points were taken from original publication and only clear data was accounted in our calculation. The information was organized in D_o, D_c, P_l, P_t, S_p, F_p, t, N, Re_{D_o} and Re_{D_c} and if one o those information could not be found, the point was not used.

Table 2: Author's correlations summary.

Author	Correlation
Gray and Webb (1986)	$j_4 = 0.14Re^{-0.328} \frac{P_t}{P_l}^{-0.502} \frac{S_p}{D_c}^{0.0312}$ $j_n = j_4 0.991 \left(2.24Re^{-0.092} \left(\frac{N}{4}\right)^{-0.031}\right)^{0.607(4-N)}$
Kim *et al.* (1999)	$j_3 = 0.163Re^{-0.369} \left(\frac{P_t}{P_l}\right)^{0.106} \left(\frac{S_p}{D_c}\right)^{0.0138} \left(\frac{P_t}{D_c}\right)^{0.13}$ $j_{1,2} = j_3 1.043 \left(Re^{-0.14} \left(\frac{P_t}{P_l}\right)^{-0.564} \left(\frac{S_p}{D_c}\right)^{-0.123} \left(\frac{P_t}{D_c}\right)^{1.17}\right)^{(3-N)}$
Pirompugd *et al.* (2006)	$j_1 = 0.6189 \left(\frac{S_p}{D_c}\right)^{-0.7834} \left(\frac{P_t}{D_c}\right)^{0.9802} Re^{\left(.3232\left(\frac{S_p}{D_c}\right)+0.04332\left(\frac{P_l}{D_c}\right)-0.07983\left(\frac{P_t}{D_c}\right)-0.6125\right)}$ $j_{2,4,6} = 0.3301 j_1 \left(\frac{S_p}{D_c}\right)^{0.4683} \left(\frac{P_l}{D_c}\right)^{0.3549} \left(\frac{P_t}{D_c}\right) 0.8906 Re^{\left(-0.3611\left(\frac{S_p}{D_c}\right)-0.01713\left(\frac{P_l}{D_c}\right)-0.01710\left(\frac{P_t}{D_c}\right)+0.2514\right)}$

Table 3: Data-base geometrical range.

Ref:	$D_c(mm)$	$P_l(mm)$	$P_t(mm)$	$F_p(mm)$	$t(mm)$	N (-)
Experimental	10.20	23.00	20.00	3.1	0.1	2
Wang *et al.* (1996)	10.23	22.00	25.40	1.74-3.21	0.13-0.20	2-6
Wang *et al.* (1997)	10.23	22.00	25.40	1.82-3.16	0.13	2-6
Wang and Chi (1998a)	7.53-10.23	12.70-19.05	21.00-25.40	1.22-2.31	0.115	1-4
Pirompugd *et al.* (2006)	8.51-10.34	19.10-22.00	19.10-22.00	1.19-3.20	0.115-0.13	1-6
Pirompugd *et al.* (2007)	8.51-10.34	19.10-22.00	25.4	1.19-3.00	0.115-0.13	1-4
Kim (2015)	5.30	11.20	19.50	1.10-1.30	0.12	1-3
Total	5.30 - 10.34	11.2 - 23.00	19.10 - 25.40	1.10 - 3.21	0.1 - 0.2	1 - 6

3.3 Correlation

Tab. (3) data was reduced using a multiple regression method with non-dimensional parameters known in the literature. The method consists in using a general equation, as Eq. (11), to adjust the non-dimensional and the constants. In this example, A, B, C and D are constants of adjustment and $C1$, $C2$ and $C3$ are geometric parameters which are chosen by trial and error and evaluating Mean Absolute Error (MAE) to check performance while the data adjustment proceed. Data reduction was performed using an particle swarm optimization algorithm. This method try to solve a problem by iteration while particles improve their predction performance for each new generation in relation to a given quality parameter. Then, Making the groups of particles converge to a local minimum solution and sweeping a space of solutions with a given speed, the algorithm thus guarantees the absolute minimum solution that in this case is the set of constants that converge for the slightest error.

$$j = AC1^B C2^C C3^D ... \tag{11}$$

4. RESULTS

It is possible to observe an improvement in the efficiency of correlations over the years. Overall results show good agreement with the prediction methods which can be more explored in the future. The suggested correlation presented outstanding results overcoming others correlation for our data-base. The new correlation presented a MAE of 12.4% for all points in the data-base. Tab. 4 present a summary and comparison of predictions methods used in this work.

4.1 Correlation

As mentioned earlier, there is still room for better performance of the correlations available in the literature. Thus, the correlation shown in Eq. (12), which was reduced as described, is capable of representing the database constructed with an accuracy of 93.15% with a deviation of ± 25%.

$$j = 0.8916Re_{D_c}^{-0.05488} \left(\frac{P_t}{P_l}\right)^{0.3836} \left(\frac{S_p}{D_c}\right)^{-0.0968} \left(\frac{P_t}{D_c}\right)^{-0.4283} \tag{12}$$

Where D_c stands for collar diameter, P_l for tube longitudinal pitch, P_t for tube transverse pitch, and S_p for fin spacing.

The obtained correlation appears to be more accurate than the others studied in this work, presenting MAE of 12.4% for the entire database. The correlation was also more accurate for the individual databases of Wang and Chi (1998a)

Table 4: Data-base MAE error comparison

Data-base	Data points	Correlation (MAE%)			
		Gray and Webb (1986)	Kim *et al.* (1999)	Pirompugd *et al.* (2006)	New correlation
Wang *et al.* (1996)	41	19.6	17.0	22.7	21.3
Wang *et al.* (1997)	24	17.0	12.0	15.4	15.4
Wang and Chi (1998a)	75	24.7	19.9	18.1	10.3
Pirompugd *et al.* (2006)	65	16.3	17.2	09.8	12.3
Pirompugd *et al.* (2007)	110	15.5	15.0	07.7	09.7
Kim (2015)	46	29.6	20.9	14.4	13.6
Current experiment	4	34.0	17.8	14.3	14.3
Total	365	20.0	17.1	13.3	12.4

and Kim (2015). Fig. (2a) presents the database of the new correlation for the experimental data. Even though the applied method select non-dimensional parameters with best precision, it is possible to observe the similarity between the proposed and the authors cited correlation's throughout the review. It is important to state that the above correlation is indicated for the range specified by the table used in its construction, Tab. (3).

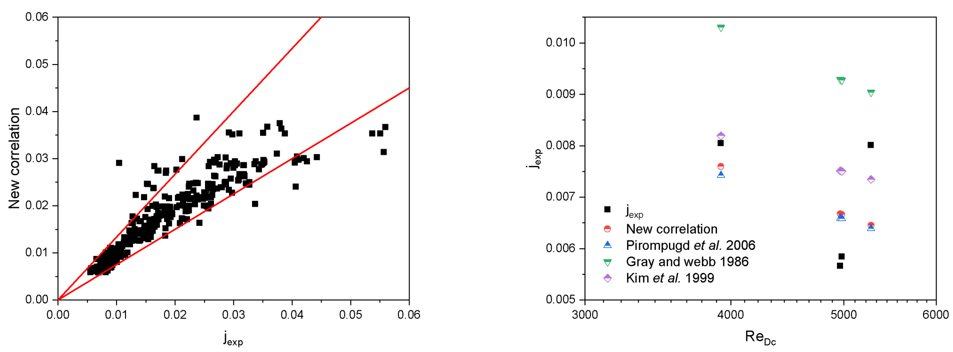
In all cases where N was used to reduce the data, the inclusion of the parameter resulted in worse precision results if compared to the other non-dimensional used, resulting in worse precision even than correlations with a smaller number of parameters. This statement points to a possible independence of N with the prediction of the Colburn factor in heat exchangers with plain fins and totally dry surface, which would be according to Wang *et al.* (1996), however a larger number of trials is needed to verify this statement.

Fig. (2b) shows the experimental points compared to the correlations used during this work. Although preliminary, the points show that the experiment follows the trend of previous works and maintains the order of magnitude, being in accordance with the correlations used. Thus, it is possible to indicate that the test bench is able to perform new experiments after some improvements.

Figure 2: Data for the proposed correlation.

(a) Data-base and new correlation with 25% of deviation.

(b) Experimental data comparison with studied correlations.



5. CONCLUSIONS

It is possible to verify a positive increase in the work on heat exchangers with plain fins, having adopted a similar methodology. The bibliographic review of heat exchangers for plain fins showed several contradictions and gaps that could be filled by the development of this work. It was possible to set up a database containing 365 experimental points, 4 of which were carried out on a dedicated bench. The preliminary results follow in agreement with some references and the numerical values of the obtained experiments are also in agreement with the literature. A correlation with increased precision has been presented, but it is still necessary to explore more tests conditions.

6. ACKNOWLEDGEMENTS

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