COMPARATIVE STUDY ON HEAT TRANSFER CALCULATION IN TRANSITION AND TURBULENT FLOW REGIME INSIDE TUBES

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***Abstract*— There exist in the technical literature several known correlations to determine the average convective heat transfer coefficient for fluid flow in single-phase inside tubes; however, no scrutiny as to their correctness has been carried out, comparing their average and maximum errors. In the present work such a comparison is carried out. Seven known correlations, those of Dittus-Boelter, Mijeev, Sieder-Tate, Petukhov, Gnielinsky, Hausen and Camaraza *et al.* are compared to such an aim by using 3296 experimental data of 36 fluids, which include water, gases, air and organic liquids. The validity range of the models was divided in six zones, additionally, the transition and turbulent regimens were considered. The comparison proves that the model by Camaraza et al. presents better indexes of correlation than the other 6 models, with lower indexes for mean absolute error and maximum error.**

***Keywords*— Single-phase, heat transfer coefficient, model, average deviation, friction factor.**

I. INTRODUCTION

Currently, to evaluate the convective heat transfer coefficient, a common practice is to use the Dittus-Boelter's correlation, developed for the determination of the average heat transfer coefficients in turbulent flows inside smooth pipes. Another very used model is the correlation by Sieder-Tate. These procedures are used in calculation and evaluation of new projects or industrial facilities; however, these correlations evidence high values of uncertainty in the results obtained with their use, coming to errors near $\pm 40\%$ (O'Neill *et al.*, 2019).

In order to improve this uncertainty, in the past century several investigations were carried out so currently in the technical literature there exist more of a dozen correlations to determine the average convective heat transfer coefficient, amongst them, the correlation by Mijeev (Camaraza-Medina *et al.*, 2017).

The model given by Petukhov, an offspring of Prandtl's analogy, provides an average error of 5% for values of $Pr \leq 200$ and 10% for $Pr > 200$, however, it is applicable only for the turbulent zone completely developed $1 \times 10^4 < Re$, (Cttani *et al.*, 2017; Rabiee *et al.*, 2018). This inconvenience was solved by Gnielinsky, modifying Petukhov´s equation and extending its use to the transition zone $2.3 \times 10^3 < Re < 1 \times 10^4$. Another available model in the literature for the turbulent transition zone is provided by Hausen (Will *et al.*, 2018). The correlations known at the present time are derived fundamentally from the analogies of Reynolds or Prandtl; the first ones present the exponential form $cRe^m Pr^n$ and the second ones a most complex structure, which includes the friction factor and the potential effect of the Prandtl number (Menni *et al.*, 2019; Mondal and Field, 2018; Medina *et al.*, 2017a).

Very recently, a model that includes characteristics of both approaches, extending the range of validity to zones of operation not covered up at the present time by the known models, and maintaining parallel a lower level of uncertainty was proposed (Camaraza-Medina *et al.*, 2019c). In the original publication of these known models, only the average error of correlation obtained in the validation is provided, which is averaged in the validity interval; however, it is not known how this error varies in different ranges. In some cases, the maximum error or the number of data that show a higher error of correlation than the average error of the model is known, (Camaraza-Medina *et al.*, 2019a; Medina *et al.*, 2017b; Chen *et al.*, 2019).

At the present time, in the known specialized literature there exist no study that provides for each model the variation of the average and maximum errors, and the number of data that correlate over the average error. For this purpose, the present work compiled 3296 experimental data of 36 fluids, which include water, gases, air and organic liquids. These experimental data were correlated with seven models known in literature (Dittus-Boelter, Mijeev, Sieder-Tate, Petukhov, Gnielinsky, Hausen and Camaraza *et al.*) A summary of these equations, their validity range and the average errors of correlation are given in (Camaraza-Medina *et al.*, 2019b; Medina *et al.*, 2018). The description and tabulation of the obtained results in the data correlation with the seven select models is the main objective of this paper.

II. MATERIALS AND METHODS

A. Required element for the comparative study

In the analyzed models, the larger status of validity is the correlation of Camaraza *et al.*, therefore, to carry out the study, its validity range is fragmented in six subintervals, detailed in Table1. In Table 1, μ_F and μ_P are the fluid dynamic viscosity at T_F and T_P, respectively.

The experimental data used in the validation of the selected model were extracted from Camaraza (2017) and summarized in Table 2. The deviation percent is developed with respect to Camaraza *et al*. model and is obtained by means of following equation, Clymer (2017), Rosenhouse (2019):

Table 1. Description of the validity range of the model.

Interval	Viscosity relation	Prandtl number
1	$0.006 < \mu_F/\mu_P \leq 12.4$	$0.65 < Pr \leq 10^2$
2	$0.006 < \mu_F/\mu_P \leq 25.6$	$0.65 < Pr \leq 5 \times 10^2$
3	$0.006 < \mu_F/\mu_P \leq 32.2$	$0.65 < Pr \leq 2 \times 10^3$
4	$0.006 < \mu_F/\mu_P \leq 44.1$	$0.65 < Pr \leq 8.1 \times 10^3$
5	$0.006 < \mu_F/\mu_P \leq 62.2$	$0.65 < Pr \leq 1.6 \times 10^4$
6	$0.006 < \mu_F/\mu_P \leq 177$	$0.65 < Pr \leq 4.71 \times 10^4$

$$D_{\%} = 100 \cdot \left(\frac{\alpha_R - \alpha_{exp}}{\alpha_R}\right) \quad (1)$$

In Eq. (1), $D_{\%}$ is the deviation percent, α_R and α_{exp} are the heat transfer coefficient in single-phase and experimental respectively, in $W/(m^2 \cdot °C)$. The mean absolute error (MAE) is obtained as (Anirudh and Dhinakaran, 2018):

$$MAE = \frac{1}{N}\sum_N \left|\frac{\alpha_R - \alpha_{exp}}{\alpha_R}\right| \quad (2)$$

In Eq. (2), N is the number of experimental data available.

Table 2. Experimental data used in the validation of the selected models, Camaraza (2017).

Source	Number of data	Fluid	l/d	$Re \times 10^3$	Pr	μ_F/μ_P	Deviation percent
I'lin (1951)	188	Air	41 162	7 6600	0.68 0.7	0.65 1.65	5.3 3.5
Volkov (1966)	218	Air	48 370	12.5 3700	0.68 0.7	0.65 1.65	6.2 -1.5
Petukhov (1963)	140	Air	39 100	15 5800	0.68 0.7	0.65 1.65	4.4 2.1
Sukomiel (1962)	44	Helium	20 50	9 40	0.71 0.72	0.22 4.5	7.1 -2.3
	67	Isobutene (2-Methylpropane)	2 60	3200 7200	0.73 0.75	0.68 1.46	9.7 -6.4
	148	Water	6 64	12 540	0.9 9.4	0.19 0.77	8.2 -7.9
Eckert (1964)	93	Turpentine	10 90	13 110	14.3 29.8	0.41 2.43	11.6 -14.7
Sabersky (1963)	44	Water	48 61	120 160	1.2 5.9	0.24 0.86	10.2 1.1
	52	Pentane	46 88	150 620	4.5 7.1	0.47 2.08	13.1 -9.6
Yakolev (1960)	39	Water	70 90	19 140	2 12	0.21 1.15	12.6 -3.9
Sabersky (1965)	62	Water	60 110	35 120	1 9.44	0.13 7.15	13.1 9.9
Sterman-Petukhov (1970)	46	Transformer oil	89 125	3.4 13.8	34.9 1530	0.01 115.2	12.7 -10.3
	29	Glycerin	89 125	2.5 9.1	1630 22650	0.018 55,4	9.2 -5.4
	52	MC Oil	66 115	5 10.4	120 9800	0,007 133,3	14.8 -17.1
	38	MK Oil	80 145	5.4 8.7	590 39000	0.011 88.7	15.8 -12.6
Kreith (1947)	31	Butyl Alcohol	38	42 78	23 30	0.08 0.45	15.3 -12.2
Ykolev*et al*. (1965)	53	Benzene	60 110	2.6 21.1	3.2 5	0.31 3.17	8.8 -4.8
Humbble (1993)	117	Gasoline	60 190	70 6900	5.5 15.1	0.22 4.4	10.4 -6.1
	181	Hydrogen	43 67	12 8200	0.65 0.73	0.48 3.28	-2.4 -8.8
Kirilov (1967)	125	Nitrogen	100 138	6 8100	0.68 0.75	0.15 6.5	9.8 1.9
Efimok (1969)	21	Carbon Dioxide	77 206	14 660	0.66 0.81	0.3 3.3	7.4 0.7
Yan-Lin (1999)	91	Water	2 420	4 250	0.94 11	0.19 0.96	9.9 -11.5
Tarashmova (2001)	26	Water	20 450	400 2500	0.94 11	0.19 0.96	13.6 -8.9
Karkalala (2012)	44	Water	18 51	1200 2800	1.2 5.9	0.24 0.96	5.3 4.5
Jung et al. (2008)	73	Transformer oil	19 150	2.8 8.1	34.9 4800	1.2 28	16.2 -7.5
Carpenter (1957)	66	Methanol	45 120	2.9 1112.1	2.2 7.7	0.1 9.9	4.4 2.1
Vasserman (1962)	112	Kerosene	30 280	6.4 52.8	1.35 2.9	0.38 2.6	7.1 -2.3
	57	Acetic acid	55 135	3.1 987.8	8.5 14.2	0.8 1.2	4.7 -3.7
	38	Acetaldehyde	65 120	3.9 52.4	2.85 4.4	0.4 2.1	8.2 -7.9

	141	Butanol	40	5.4	22.5	0.04	11.6
			160	822.6	3860	24.6	-16.7
	187	Aniline	50	4.4	11.5	0.08	9.7
			280	1024.2	111	12.35	-3.5
	37	Carbon Disulfide	48	13.8	2.3	0.59	10.2
			125	76.9	3.2	1.68	-1.1
	23	Ciclohexane	85	36.1	11	0.5	2.3
			220	89.4	19.9	1.9	-1.7
	113	Ethanol	80	21.4	6.9	0.049	5.2
			125	1513.8	68.4	20.5	7.4
	71	Ethyl ether	70	580	3.5	0.3	4.2
			135	2560	7.3	3.6	8.1
	25	Ethylamine	80	12.1	5.1	0.55	3.2
			100	17.8	8.3	1.8	-6.1
Sherwood (1967)	31	Propylene	60	125	2.8	0.27	9.1
			120	284	3.2	3.66	-4.8
	36	Dodecane	70	72	10.7	0.4	11.1
			250	96	28.2	3.3	-12.4
	53	Decane	65	16	6.8	0.25	2.3
			135	47.2	17.1	4.1	-7.8
	63	Ethylene glycol	90	6.3	69	0.12	7.1
			165	12.1	510	8.1	-9.3
Gordon (1937)	26	Oil olive	85	2.7	700	0.3	9.1
			120	7.6	810	2.9	-11.4
Gordon (1939)	29	Toluene	70	3.9	4.7	0.1	11.6
			150	27.2	21.1	7.8	-9.4
Mudawar et al. (2012)	166	Engine Oil	30	2.4	84	0.006	14.1
			180	10.2	47100	177	-19.4
For all sources above	3296		2.0	2.4	0.65	0.006	16.2
			450	8200	47100	177	-19.4

Table 3. Summary of the N values used by zone.

Interval	$2.3 \times 10^4 \leq Re < 10^4$	$10^4 \leq Re < 8.2 \times 10^6$
1	219	439
2	397	815
3	516	1147
4	627	1434
5	799	1735
6	1103	2193

In order to accomplish this correlation study, the experimental available data were separated in two groups (see Table 3), for transition and turbulent zones.

The study was carried out with 3296 experimental data. In Table 3 the N values of experimental data available for each validity range of the model are summarized (in agreement with the classification given in Table 1).

The experimental available data are grouped in the six intervals shown in Table 1 and thus the data of each zone with the seven models selected for this study are correlated, obtaining for each model the percentage values of data that correlates under *MAE* values (D_{mean}), the *MAE* values and the maximum error (E_{max}).

III. ANALYSIS OF RESULTS

A. Summary of the main results obtained in the evaluation of the transition zone

In Figs. 1 to 3, the values of *MAE*, E_{max} and D_{mean} obtained in the correlation developed between available experimental data and selected models are given in graphical form.

The study shows that in the transition zone, the fundamentals results used in the comparison concentrate on three fundamental elements, described early (*MAE*, $E_{\max}$ and D_{mean}). In these for $2.4 \times 10^3 \leq Re < 10^4$, it is confirmed that the model given by Camaraza *et al.* have the best *MAE* adjustment values, showing an average error of 12.1% and 13.6%, for 88.0% and 78.3% of the available data for Zones 1 and 6, respectively.

In the specialized literature it is established that Gnielinsky's model correlates with an average error of 10%; however, the results obtained in the present study show an average error of 7.5% and 14.8% for 85.2% and 76.6 % of the data for Zones 1 and 6, respectively, proving that the values obtained in the present study are slightly higher to the values commonly attributed in the literature.

The most unfavorable indicators are obtained using the models of Dittus-Boelter and Mijeev, which provide *MAE* values respectively of 38.4% and 36.1% for 64.5% and 68.1% of the experimental data, respectively. Hausen's model allows to obtain convenient results, with *MAE* values of 19.3% in 75.1% of the examined data, which agrees well with those results given by Will *et al.* (2018).

The correlations of Petukhov and Sieder-Tate are not valid in this interval; however, they provide an adequate result, with *MAE* values of 24.6 and 29.4% for 72.4 and 70.5% of the experimental data, respectively; this indicates that they can be used for rapid estimations of the heat transfer coefficients in the transition zone, which confirms the recommendations given by Liu *et al.* (2018).

In the transition zone, it was found for the examined models a similarity of the criteria D_{mean}. In each equation, the adjusted curve was constructed on the basis of the D_{mean} values obtained for each zone. All the curves have one maximum point, located in Zone 1 (see Fig. 3), and from there on all curves present an asymptotic decrease near to an exponential curve ruled by the func-

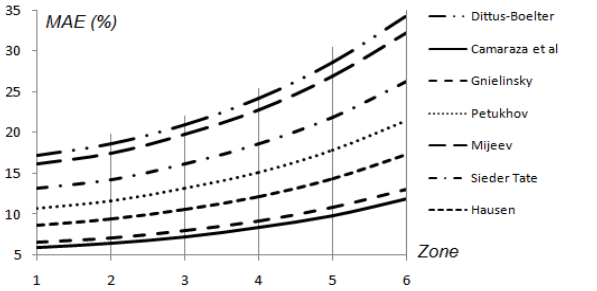

Figure 1: *MAE* values in the correlation data (transition zone).

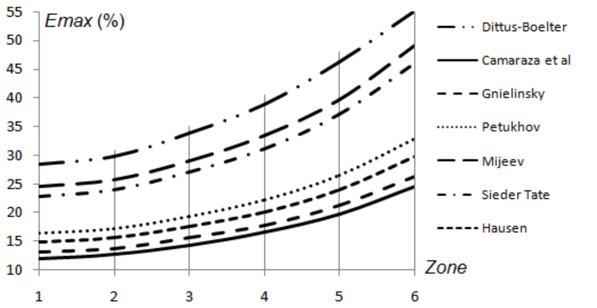

Figure 2: E_{max} values in the correlation data (transition zone).

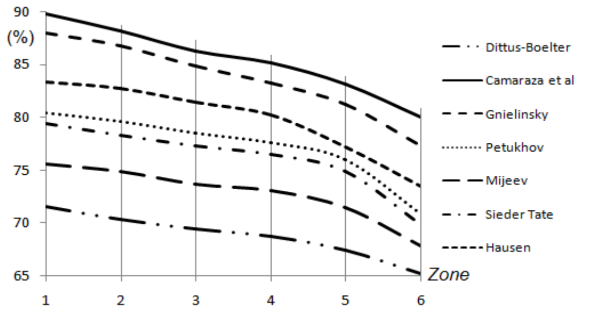

Figure 3: D_{mean} values in the correlation data (transition zone).

tion $ae^{-0.02 \cdot z}$, in which, a is the D_{mean} in Zone 1, and z is the number of the zone evaluated in the correlation study.

The model developed by Camaraza *et al.* and Gnielinsky, shows the best D_{mean} index, with 88.0% and 85.2% respectively in Zone 1, while these values reduce to 79.3% and 76.3% for Zone 6. On the contrary, the models of Mijeev and Dittus-Boelter have the more unfavorable indexes, with 74.6% and 69.7% respectively in Zone 1, decreasing to 67.1% and 63.0% for Zone 6.

The correlations by Petukhov and Sieder-Tate provide favorable results, with 80.4% and 78.9% respectively in Zone 1, while these values are reduced to 71.9% and 69.6% for Zone 6. Hausen's model gives D_{mean} values laying between the intervals of the ranges ruled by the Gnielinsky and Sieder-Tate correlations, with 83.3% and 74.2% in Zones 1 and 6, respectively.

The specialized literature does not count with reports that suggest the possible maximum executed error with the use of a determined model. In the present study the value of $E_{\max}$ generated with the use of every model for the six studied zones was obtained, by means of the correlation made between the experimental available data and the models selected.

The model developed by Camaraza *et al.* and that by Gnielinsky, show the best $E_{\max}$ index, with 12.3% and 13.4% respectively in Zone 1, while these values increase to 24.6% and 26.5% for Zone 6. On the contrary, the most unfavorable indicators are obtained with the correlations of Mijeev and Dittus-Boelter, which provide $E_{\max}$ values of 24.5% and 28.5% respectively for Zone 1, increasing to 49.2% and 55.1% in Zone 6.

The models by Hausen, Petukhov and Sieder-Tate provide fairly acceptable adjustments of correlation, with $E_{\max}$ values of 14.9%, 16.4% and 22.9% respectively in Zone 1, while these values increase to 29.8%, 33.1% and 46.2% for Zone 6.

When checking the available literature, it is possible to confirm that of the studied models, only three are valid for the transition zone (Hausen, Gnielinsky and Camaraza *et al.*),

However, in the present study it was demonstrated that the models by Petukhov and Sieder-Tate can be used reservedly to determine the heat transfer coefficients in the transition regime, being preferable not to extend their use beyond Zones 1 and 2.

B. Summary of the main results obtained in the evaluation of the turbulent zone

In Fig. 4 to Fig.6 the values of *MAE*, E_{max} and D_{mean} obtained in the correlation developed between the available experimental data and the selected models in the turbulent zone are given in graphical form. It clearly can be concluded that in the turbulent zone, the fundamental results used in the comparison concentrate on three fundamental elements, described early (*MAE*, $E_{\max}$ and D_{mean}). In Figs. 4 to 6, for $10^4 \leq Re < 8.2 \times 10^6$, it is confirmed that the model by Camaraza *et al.* have the best *MAE* adjustment values, showing an average error of 7.1% and 12.4% for 89.5% and 80.2% of the available data for Zones 1 and 6, respectively.

In the specialized literature it is established that the models by Petukhov and Gnielinsky correlate with an average error of 5% and 10% for Zones 1 and 6, respectively; however, the results obtained in the present study for Petukhov's model show *MAE* values of 7.4% and 13.5% for 87.1% and 78.3% of the experimental data for Zones1 and 6 respectively, while for the Gnielinsky model the *MAE* values are 7.8% and 14.6% for 88.2% and 78.8% of the data for Zones 1 and 6. These results allow checking that the values obtained in the present study are slightly higher to the values commonly attributed to these models in the literature.

The most unfavorable indicators are obtained with the Dittus-Boelter and Sieder-Tate models. The first provides *MAE* values of 21.6% and 39.3% for 74.2% and 66.7% of the data, for Zones 1 and 6, respectively. The second model shows *MAE* values of 14.3% and 36.5% for 80.9% and 72.4% of the experimental data, for Zones 1 and 6, respectively.

The models by Mijeev and Hausen allow obtaining convenient correlation results. Hausen's model provides *MAE* values of 9.8% and 20.4% for 85.2% and 74.2% of the experimental data, for Zones 1 and 6, respectively.

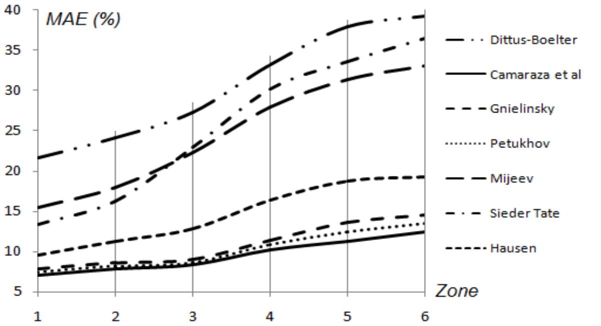

Figure 4: *MAE* values in the correlation data (turbulent zone).

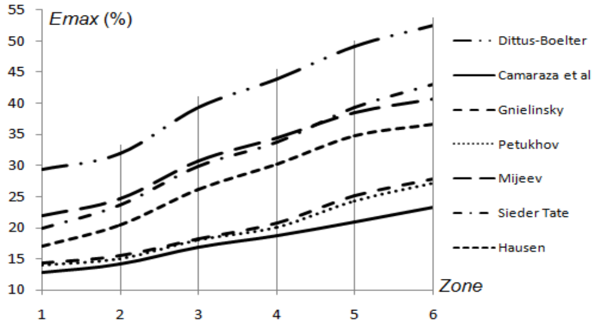

Figure 5: E_{max} values in the correlation data (turbulent zone).

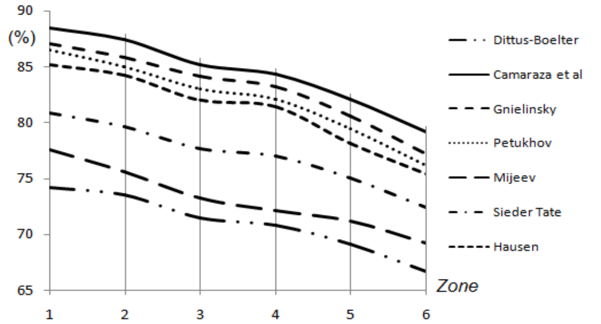

Figure 6: D_{mean} values in the correlation data (turbulent zone).

The model by Mijeev shows *MAE* values of 15.5% and 32.8% for 77.6% and 70.2% of the experimental data, for Zones 1 and 6, respectively.

In the turbulent zone, a similarity of the criteria D_{mean} was found for the models examined. For each correlation, the adjusted curve was constructed on the basis of the D_{mean} values obtained for each zone. All the curves have one maximum point, located in Zone 1 (see Fig. 6), and here thereafter they present an asymptotic decrease near to an exponential curve ruled for the function $ae^{-0.022\cdot z}$, in which, a is the D_{mean} in Zone 1, and z is the number of the zone evaluated.

The models developed by Camaraza *et al.*, Gnielinsky and Petukhov, show the best D_{mean} index, with 89.5%, 88.1% and 87.1% respectively for Zone 1, while these values reduce to 80.2%, 78.8% and 78.3% for Zone 6.

The correlations by Mijeev, Sieder-Tate and Dittus-Boelter have the most unfavorable indexes D_{mean}, with 77.6%, 80.9% and 74.2% respectively in Zone 1, while these values reduce to 70.2%, 72.4% and 66.7% for Zone 6. Hausen's correlation gives D_{mean} values laying between the intervals of the ranges ruled by the Petukhov and Sieder-Tate correlations, with 85.2% and 76.4% in Zones 1 and 6, respectively.

The specialized literature does not count with reports that suggest the possible maximum executed error with the use of a determined model. In the present study the value of E_{max} generated with the use of every model for the six studied zones was obtained, by means of the comparison made between experimental available data and the seven models under study.

The models developed by Camaraza *et al.*, Petukhov and Gnielinsky, show the best E_{max} index, with 12.8%, 13.9% and 14.4% respectively for Zone 1, while these values increase to 23.2%, 27.1% and 28.2% for Zone 6. The correlations by Mijeev, Sieder-Tate and Dittus-Boelter have the most unfavorable indexes E_{max}, with 21.9%, 19.9% and 29.4% respectively in Zone 1, while, these values increase to 40.8%, 43.0% and 52.5% for Zone 6. The model by Hausen provides fairly acceptable adjustments, with E_{max} values of 17.0% and 36.6%, respectively in Zones 1 and 6.

IV. CONCLUSIONS

In this paper, seven existing models that determine the convective heat transfer coefficient were compared. For this purpose, 3296 experimental data of different fluids were correlated. The validity range of the models was divided in six zones, additionally, two regimens, transition and turbulent were considered.

For the transition zone 1103 experimental data were used, finding that the best adjustment was obtained with the correlation by Camaraza *et al.*, with a *MAE* value of 6.1% for 88.0% of the data and 12.1% of E_{max} for Zone 1, while for Zone 6, the *MAE* value is equal to 13.6% for 79.3% of the data and 24.6% for E_{max}. The weaker adjustment was achieved with the model of Dittus-Boelter, with a *MAE* value of 17.2% for 71.8% of the data and 28.5% for E_{max} for Zone 1, while for Zone 6, the *MAE* is equal to 38.4% for 64.5% of the data and 55.1% for E_{max}. Other models that present reasonable adjustments are those of Gnielinsky and Hausen, the first has a global *MAE* of 14.8% for75.6% of the data, while the second has a MAE of 19.3% for 75.0% of the data.

For the turbulent zone 2193 experimental data were used, finding that the best adjustment was obtained with the model by Camaraza *et al.*, with a *MAE* of 7.1% for 89.5% of the data and 12.8% for E_{max} for Zone 1, while for Zone 6, the *MAE* is equal to 12.4% for 80.2% of the data and 23.2% for E_{max}. The weaker adjustment was achieved with the model of Dittus-Boelter, with a *MAE* of 21.2% for 74.2% of the data and 29.4% for E_{max} for Zone 1, while for Zone 6, the *MAE* is equal to 39.3% for 66.7% of the data and 52.5% for E_{max}. Other models that present reasonable adjustments are the models by Petukhov and Gnielinsky; they have a global *MAE* of 13.5% for78.3% of the data and 14.6% for 78.8% of the data, respectively.

In this study, the models recognized in the literature as more precise (Petukhov and Gnielinsky), showed a slightly larger uncertainty than the results obtained with the model of Camaraza *et al*. Thus, the model by Camaraza *et al*. is a better correlation, with a much better adjustment with the experimental data. Its use leads to a lower value of uncertainty in the calculation of the heat transfer coefficients in the turbulent and transitional regimes.

REFERENCES

Anirudh, K. and Dhinakaran, S. (2018) Effects of Prandtl number on the forced convection heat transfer from a porous square cylinder. *Int. J. Heat Mass Transf.* **126**, 1358-1375.

Camaraza, Y. (2017) *Introducción a la termotransferencia*, Editorial Universitaria, La Habana.

Camaraza-Medina, Y., Rubio-Gonzales, A.M., Cruz-Fonticiella, O.M. and Garcia-Morales, O.F. (2017) Analysis of pressure influence over heat transfer coefficient on air cooled condenser. *J. Eur. Syst. Autom.* **50**, 213-226.

Camaraza-Medina, Y., Hernández-Guerrero, A., Luviano-Ortiz, J.L., Mortensen-Carlson, K., Cruz-Fonticiella, O.M. and García-Morales, O.F. (2019a) New model for heat transfer calculation during film condensation inside pipes. *Int. J. Heat Mass Transf.* **128**, 344-353.

Camaraza-Medina, Y., Mortensen-Carlson, K., Guha, P., Rubio-Gonzales, A.M., Cruz-Fonticiela O.M. and Garcia-Morales, O.F. (2019b) Suggested model for heat transfer calculation during fluid flow in single phase inside pipes (II). *Int. J. Heat Technol.* **37**, 257-266.

Camaraza-Medina, Y., Cruz-Fonticiella, O.M. and García-Morales, O.F. (2019c) New model for heat transfer calculation during fluid flow in single phase inside pipes. *Therm. Sci. Eng. Prog.* **11**, 162-166.

Chen, Z.Y., Cheng, M., Liao, Q., Ding, Y.D. and Zhang, J.N. (2019) Experimental investigation on the air-side flow and heat transfer characteristics of 3-D finned tube bundle. *Int. J. Heat Mass Transf.* **131**, 506-516.

Clymer, J.R. (2017) Mathematics of complex adaptive systems. *Int. J. Des. Nat. Ecodyn.* **12**, 377-384.

Cttani, L., Bozzoli, F. and Raineri, S. (2017) Experimental study of the transitional flow regime in coiled tubes by the estimation of local convective heat transfer coefficient. *Int. J. Heat Mass Transf.* **112**, 825-836.

Liu, F., Cai, Y., Wang, L. and Zhao, J. (2018) Effect of nanoparticle shape on laminar forced convective heat transfer in curved ducts using two-model. *Int. J. Heat Mass Transf.* **116**, 825-836.

Medina, Y.C., Khandy, N.H., Fonticiella, O.M.C. and Morales, O.F.G. (2017a) Abstract of heat transfer coefficient modelation in single-phase systems inside pipes. *Math. Model. Eng. Prob.* **4**, 126-131.

Medina, Y.C., Fonticiella, O.M.C. and Morales, O.F.G. (2017b) Design and modelation of piping systems by means of use friction factor in the transition turbulent zone. *Math. Model. Eng. Prob.* **4**, 162-167.

Medina, Y.C., Khandy, N.H., Carlson, K.M., Fonticiella, O.M.C. and Morales, O.F.G. (2018) Mathematical modeling of two-phase media heat transfer coefficient in air-cooled condenser systems. *Int. J. Heat Technol.* **36**, 319-324.

Menni, Y., Chamkha, A.J., Zidani, C., Benyoucef and B. (2019) Heat and nanofluid transfer in baffled channels of different outlet models. *Math. Model. Eng. Prob.* **6**, 126-131.

Mondal, S. and Field, R.W. (2018) Theoretical analysis of the viscosity correction factor for heat transfer in pipe flow. *Chem. Eng. Sci.* **187**, 27–32.

O'Neill, L.E., Balasubramaniam, R., Nahra, H.K., Hasan, M.M. and Mudawar, I. (2019) Flow condensation heat transfer in a smooth tube at different orientations: experimental results and predictive models. *Int. J. Heat Mass Transf.* **140**, 533-563.

Rabiee, R., Désilets, M., Proulx, P., Ariana, M. and Julien, M. (2018) Determination of condensation heat transfer inside a horizontal smooth tube. *Int. J. Heat Mass Transf.* **124**, 816-828.

Rosenhouse, G. (2019) From nature and basic scientific results to modern engineering applications. *Int. J. Des. Nat. Ecodyn.* **14**, 249-263.

Will, J.B., Kruyt, N.P. and Venner, C.H. (2017) An experimental study of forced convective heat transfer. *Int. J. Heat Mass Transf.* **109**, 1059-1067.

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