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Abstract of heat transfer coefficient modelation in single-phase systems inside pipes

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ABSTRACT

This paper presents the results of the continuity of the research process carried out in the center of environmental and energy studies that belonged to the Technical Sciences Faculty of the University of Matanzas related to obtaining non - dimensional models for the determination of the average coefficient of heat transfer in turbulent flows inside smooth and straight tubes. The research consists of a regression analysis performed between the Reynolds number, the Prandtl number and the friction factor, using for this purpose experimental data reported by different authors, establishing a comparison with the equations of Petukhov and Gnielinsky, exact and referenced in the known literature, obtaining that there are no significant differences, due to the high similarity between the results obtained from these models in the studied range of the work parameters, although the divergence between the experimental values and those obtained by the proposed model is slightly smaller.

Keywords: Average Coefficient, Heat Transfer, Model, Regression.

1. INTRODUCTION

It is a widespread practice and recommended in a large part of the literature on the subject to perform the calculation of the average heat transfer coefficients in single phase media using the expressions of Dittus-Boelter [13] Or the improved version of Sieder - Tate [11], provided that it is in the presence of a turbulent flow and that it circulates through the interior of straight ducts. This procedure is a necessity for many project calculations or evaluation of industrial facilities. However, these expressions have a high dispersion value of the obtained results to the real values of the systems analyzed, being in the literature consulted errors of the order of $\pm 25\%$.

In the 1960s, [1], at the Moscow Institute of Energy, an equation was obtained, which was derived basically from experimental point adjustments, which were later implemented at the Analogy of Prandtl. The equation obtained is known in the specialized literature as Petukhov equation, in recognition of the leader of the research group that developed this important research for the science of the term convective transference. This equation reduces the absolute mean error as a function of the number of Prandtl, so that:

$$\begin{aligned} &if \quad \Pr \le 200 \quad Error < 5\% \\ &if \quad \Pr > 200 \quad Error \le 10\% \end{aligned}$$

The Petukhov equation is described by the following expression:

$$Nu = \left(\frac{\left(\frac{f}{8}\right) \mathrm{Re}\,\Pr}{C + 12{,}7\sqrt{\frac{f}{8}}\left(\Pr^{\frac{2}{3}} - 1\right)} \left(\frac{\mu_P}{\mu_F}\right)^N \right) \tag{1}$$

$$C = 1{,}07 + \frac{900}{\mathrm{Re}} - \frac{0{,}63}{(1 + 10\Pr)}$$

where N is a constant that depends on the thermal process being evaluated, it will be equal to -0.11 for heating and -0.25 for cooling.

The Darcy's friction factor in equation (1) is determined by the correlation of Filonenko, which is given by:

$$f = (1{,}821\ Log(\mathrm{Re}) - 1{,}64)^{-2} \tag{2}$$

Expression (1) is just to:

$10^4 < \text{Re} < 5 \cdot 10^6$; $0{,}5 \le \text{Pr} \le 2000$; $0{,}025 \le \left(\frac{\mu_P}{\mu_F} \right) \le 12{,}5$

The results obtained using the expression (1), although the application is more laborious, have a lower dispersion, and, therefore, a smaller safety margin in the design calculations.
A major drawback of expression (1) is its applicability range, since this is only valid for a fully developed turbulent flow regime, $10^4 \le \text{Re}$, so that the facilities that the flow operate in the transition zone, that is, in the interval $2{,}3 \cdot 10^3 \le \text{Re} < 10^4$, non- applicable. This problem was later solved by Gnielinsky [15], who modified equation (1) by adjusting it to experimental data that do take into account the transition flow zone. This expression is represented as:

$$Nu = \left(\frac{\left(\frac{f}{8}\right)(\text{Re} - 1000)\text{Pr}}{1 + 12{,}7\sqrt{\frac{f}{8}}\left(\text{Pr}^{\frac{2}{3}} - 1\right)} \left(\frac{\mu_P}{\mu_F} \right)^N \right) \tag{3}$$

The notations used in equation (3) are identical to those used in expression (1).
Expression (3) is just to:

$3 \cdot 10^4 < \text{Re} < 5 \cdot 10^6$; $0{,}5 \le \text{Pr} \le 2000$; $0{,}025 \le \left(\frac{\mu_P}{\mu_F} \right) \le 12{,}5$

Another expression that provides a good approximation is Sandall's equation [4], which provides very good results in the calculation of the average coefficient of convection heat transfer in confined turbulent flows, provided that the evaluated flow is a liquid of medium viscosity (water) with an average error of the order of 8%. In the specialized literature a more numerous group of expressions of empirical or semi empirical character can be found, this is caused mainly by the stochastic nature of the turbulent flow, what makes impossible the development of expressions of analytical character and it becomes necessary to resort to the Experiments and to the theory of dimensional analysis to later formulate by means of statistical methods calculus expressions that allow to obtain of approximated form the value of the average coefficient of heat transfer.

2. MATERIALS AND EMPLOYED METHODS

2.1 Methods of dimensional analysis and procedures.

The heat transfer film coefficient in a turbulent flow regime is associated to a series of variables independent of the flow to be analyzed, which are:
1- The density
2- Dynamic viscosity
3- Specific heat at constant pressure
4- The thermal conductivity
In addition, it will depend on the conditions of the environment in which the fluid flow moves, they are:
1- The diameter of the conduit
2- The velocity of the fluid mass inside the duct
3- The length of the conduit
4- The grain size of equivalent sand of the duct wall, (if you want to take into account the roughness of the pipe)

In the turbulent flow, unlike the laminar regime, there is no ordered pattern of flow lines, therefore the effect of viscous forces is greater than the gravitational forces, which generates that the effect of the latter is Normally neglected in the analyzes.
From the above explained and through the implementation of the techniques of the theory of dimensional analysis can obtain the relationship between these variables to find out how to group the experimental data that are arranged for its subsequent correlation in an empirical relationship that Allows predicting the value of the heat transfer film coefficient. This dependency will then be a function of several dependent variables, as shown in the following expression:

$$\alpha = F(V, T_P, T_F, d, \rho, \mu, C_P, \lambda, l, e) \tag{4}$$

Applying the inter national system of units the following system of notations is obtained:

$$\begin{aligned} &Dough(kg) = M \qquad length(m) = L \\ &temperature(^0C) = \theta \quad ; \quad time(S) = T \end{aligned} \tag{5}$$

Substituting the notations shown in (5) into the functional dependence given in (4) above is a summary of units involved in the dimensional analysis. This summary will be shown in Table 1

Table 1. Summaries of units involved in dimensional analysis

Physical property	Measurement Unit	Dimensional Unit
α	$\frac{W}{m^2\,{}^0C} = \frac{kg}{S^3\,{}^0C}$	$MT^{-3}\theta^{-1}$
V	m/s	LT^{-1}
d	m	L
ρ	kg/m^3	ML^{-3}
μ	$Pa \cdot s = kg/sm$	$MT^{-1}L^{-1}$
Cp	$\frac{J}{kg^0C} = \frac{m^2}{S^2\,{}^0C}$	$L^2T^{-2}\theta^{-1}$
λ	$\frac{W}{m^0C} = \frac{kgm}{S^3\,{}^0C}$	$MLT^{-3}\theta^{-1}$
l	m	L
e	m	L

By using the techniques of dimensional analysis [2], we conclude that the average coefficient of heat transfer in turbulent regime can be obtained by the appropriate combination of dimensionless groups, as well As constants and exponents that affect these dimensionless groups.

2.2 Application of the Prandtl analogy to the formulation of the new model

Prandtl, [13] in his analysis to deduce his analogy, assumed that the flow is divided into two zones, a viscous zone and a turbulent zone. In his analysis he makes the additional assumption that turbulent diffusivities predominate in the turbulent zone. Without showing here the original deductions provided by Prandtl, the conclusive expression of his analogy will be given directly, which is described by the following formula:

$$Nu = \frac{\frac{f}{8}\operatorname{Re}\operatorname{Pr}}{1+5\sqrt{\frac{f}{8}}(\operatorname{Pr}-1)} \qquad (6)$$

Von Karman [14] showed that equation (6) is the reference or starting point for the formulation of an expression to determine the coefficient of heat transfer in confined turbulent flows. In order to do this, he extended the work of his predecessors even further by extending the analogy of Prandlt, dividing the field of flow into three different sublayers, which are:

1- The viscous sublayer
2- The transition sublayer
3- The turbulent sub-layer

Table 1. Comparison among equation (6) and some experimental data for horizontal, vertical and inclined tubes

Source	Number of Data	Fluid	l/d	Re. 10^3	Pr	μ_P/μ_F	Deviation Percentage (%)
I'lin (1951)	48	Air	41 62	7 60	0.7	-	5.3 4.5
Volkov (1966)	120	Air	48 370	12.5 370	0.7		6,2 1,5
Petukhov (1963)	140	Air	39	15 280	0.7		4,4 2,1
Sukomiel (1962)	44	Helium	20 50	9 40	0,67		7,1 -2,3
	67	Air	2 60	320 720	0.7		4,7 -3,7
	148	Water	6 64	12 540	0,9 9,4	0.19 0.77	8,2 -7,9
Eckert (1964)	93	Water	10 30	13 110	1,5 8	0.19 0.72	11,6 -6,7
Sabersky (1963)	33	Water	48 61	120 160	1.2 5.9	0.24 0.86	9,7 -3.5
	52	Water	46.2	150	1.2 5.7	0.35 0.98	10,2 1,1
Yakolev (1960)	39	Water	70 90	19 140	2 12	0.21 1.15	11,1 -9,6
Sterman-Petukhov (1970)	41	Transformer Oil	89 125	3,4 160	34.9 5200	1.2 42.2	12,6 -3,9
	29	glycerine	89 125	10 100	430 12500	0,025 16	13,1 9,9
	49	MC Oil	66 88	5 44	34 140	1.6 38	12,5 -6,3
	27	Transformer Oil	88	5.4 14	39 61	1.2 8.6	9,2 -5,4
Kreith (1947)	20	Butyl Alcohol	38	42 78	23 30	0.08 0.45	11,8 9,1
Ykolev et al. (1965)	50	Water	60 80	19 123	2 12	0.19 0.78	6.1 -4.8
Humbble (1993)	113	Air	30 120	7 6900	0.7		5,3 2,2
	181	Hydrogen	43 67	6 8200	0,66 0,71		8,8 -4,8
Kirilov (1967)	25	Nitrogen	100 138	6 160	0,74 0,69		7,4 -2,1
Efimok (1969)	19	Carbon Dioxide	77 206	14 660	2.4 16.8		-2.4 -8.8
Yan-Lin (1999)	91	Water	2 420	4 250	0,94 11	0.19 0.96	9,8 1,9
Tarashmova (2001)	23	Water	20 410	400 2500	0,94 11	0.19 0.96	7,4 0,7
Karkalala (2012)	44	Water	18 51	1200 2800	1.2 5.9	0.24 0.96	9,9 -1.5
Jung et al. (2008)	71	Transformer Oil	19 150	2.8 110	34.9 4800	1.2 28	13,6 -8,9
For all sources above	1567		2,0 420	2.8 8200	0,67 12500	0.025 42.2	

Von Karman made suppositions similar to those of his mentor Prandtl on the relative magnitudes of the molecular and turbulent diffusivity of the heat and the variations in the amount of movement in the viscous sublayer and in the turbulent zone, also incorporating the effects of the sublayer Of transition, considering that the molecular and turbulent diffusivity of this sublayer, were of the same order of magnitude. This last deduction was used by Petukhov [2] when deducing the exponent of the present term in the denominator that takes into account the variations of the molecular diffusivity, that is, the number of Pr, finding that this exponent is equal to 2/3. A disadvantage that presents the equations of Petukhov and Gnielisky is the range of applicability, since for high Reynolds numbers, is for, these models are not valid.

A great number of experimental papers on heat transfer in turbulent pipe flow have been published. Unfortunately, in many cases measurement accuracy was not high; therefore, heat transfer coefficients obtained experimentally often contain substantial errors which are difficult to estimate. Little experimental data of rather high accuracy have been reported in many works. Mainly heat transfer for air and water flow has been measured, i.e., approximately over a range of 0.7-10 for Prandtl numbers.

This was the cause that encouraged the author of the present to try to obtain a model that was as accurate as the previous equations, while having a greater range of applicability.

After the generalization of many experimental data generated by various authors, [13], among others, a total of 17468 experimental points Which have a total of 1567 points that are included in the non-validated zone of the models already mentioned above. The experimental values used in this work are summarized in table A.1.

A convenient adjustment to expression (6) facilitates that these experimental points not contemplated in the validity zone of the model can be considered now, extending the applicability range of the same.

The new proposed equation responds to the following formulation:

$$Nu = \frac{\left(\mathrm{Re}_d - 10^D\right)\mathrm{Pr}}{A \times B^2 - C \times B\left(1 - \mathrm{Pr}^{2/3}\right)}\left(1 + \left(\frac{d}{l}\right)^{2/3}\right)\left(\frac{\mu_P}{\mu_M}\right)^N \qquad (7)$$

The notations used in equation (7) are already known, as well as the values of the exponents N, for cases of heating or cooling, which were given prior to exposing the relation (1). In equation (7) constants A, B C and D will depend on the dimensionless number of Reynolds, establishing two intervals of dependencies, the first interval for the transition zone, $2{,}3 \cdot 10^3 < \mathrm{Re} < 10^4$ and the second intervals to $10^4 \le \mathrm{Re} \le 8{,}2 \cdot 10^6$.

To the first intervals $2{,}3 \cdot 10^3 < \mathrm{Re} < 10^4$ It is true that:

$$A = 75{,}44 \quad ; \quad B = Log\left(\frac{\mathrm{Re}^{0{,}56}}{3{,}196}\right) \quad , \quad C = 104$$

$$D = -0{,}0272Y^2 + 0{,}2006Y + 2{,}6322 \quad , \quad Y = Log(\mathrm{Re})$$

While for the second interval $10^4 \le \mathrm{Re} \le 8{,}2 \cdot 10^6$:

$$A = 90{,}415 \quad ; \quad B = Log\left(\frac{\mathrm{Re}^{0{,}56}}{3{,}196}\right) \quad , \quad C = 116{,}74$$

$$D = 0$$

Equation (7) is just to:

$2{,}3 \cdot 10^3 < \mathrm{Re} < 8{,}2 \cdot 10^6$; $0{,}5 \le \mathrm{Pr} \le 1{,}26 \cdot 10^4$; $0{,}025 \le \left(\frac{\mu_P}{\mu_F}\right) \le 42{,}2$

It can already be verified a priori that the new expression is an equation that encompasses a greater range of validity, only need to be as precise as expressions (1) and (2). To do this, a correlation of values obtained from the use of (7) and available experimental data was performed, fragmenting the applicability domain into 10 validity subdomains, and then determining the mean error%, as well as that part of the total values in the analyzed subinterval correlates below the mean error. The results obtained are summarized in Tables 2 and 3 for the first and second interval respectively.

Table 2. Correlation adjustments with the experimental data for the first range of values available for equation (7)

$2300 < \mathrm{Re} < 10^4$		
$0 < \left(\frac{\mu_P}{\mu_M}\right) \le 12.42$	$0.6 \le \mathrm{Pr} < 100$	*error* $< 6.18\%$ 92,32 % data
$\left(\frac{\mu_P}{\mu_M}\right) \le 18.35$	$\mathrm{Pr} < 200$	*error* $< 6.96\%$ 91,42 % data
$\left(\frac{\mu_P}{\mu_M}\right) \le 22.2$	$\mathrm{Pr} \le 2 \cdot 10^3$	*error* $< 8.74\%$ 90,14 % data
$\left(\frac{\mu_P}{\mu_M}\right) \le 34.16$	$\mathrm{Pr} \le 8{,}1 \cdot 10^3$	*error* $< 9.96\%$ 88,35% data
$\left(\frac{\mu_P}{\mu_M}\right) \le 42.2$	$\mathrm{Pr} \le 1{,}26 \cdot 10^4$	*error* $< 10.74\%$ 86,42% data

Table 3. Correlations with experimental data for the second range of values available for equation (7)

$10^4 \le \mathrm{Re} < 8{,}2 \cdot 10^6$		
$0 < \left(\frac{\mu_P}{\mu_M}\right) \le 12.36$	$0.6 \le \mathrm{Pr} < 100$	*error* $< 6.24\%$ 89,36% data
$\left(\frac{\mu_P}{\mu_M}\right) \le 19.41$	$\mathrm{Pr} < 200$	*error* $< 7{,}82\%$ 88,35% data
$\left(\frac{\mu_P}{\mu_M}\right) \le 26{,}48$	$\mathrm{Pr} \le 2 \cdot 10^3$	*error* $< 8{,}31\%$ 87,12% data
$\left(\frac{\mu_P}{\mu_M}\right) \le 33{,}32$	$\mathrm{Pr} \le 8{,}1 \cdot 10^3$	*error* $< 10{,}17\%$ 86,31% data
$\left(\frac{\mu_P}{\mu_M}\right) \le 42.2$	$\mathrm{Pr} \le 1{,}26 \cdot 10^4$	*error* $< 11{,}23\%$ 84,02% data

As can be seen in Table 2 for the first validity range, $2300<\mathrm{Re}<10^4$, The expression correlates with an average error of 10.74%, in 86.42% of the available experimental data, so that the obtained adjustment is considered excellent, very similar to those obtained by using equation (2), Which should be clarified that it cannot be used for Pr> 2000. It is also observed that for values of Pr <200, the mean error obtained is 6.96% for 91.42% of the available data, which brings it numerically to the 5% reported by Petukhov and Gnielinsky.

In Table 3 for the second range of validity $10^4 \leq Re < 8{,}2 \cdot 10^6$, the expression correlates with an average error of 11.23%, in 84.02% of the available experimental data, so the adjustment obtained is considered to be excellent, very similar to those obtained by using equation (2), which should be clarified that it cannot be used for Pr> 2000. It is also observed that for values of Pr <200, the mean error obtained is 6.24% for 89.36% of the available data, which brings it numerically to the 5% reported by Petukhov and Gnielinsky

As shown in Tables 2 and 3, it has just been shown that equation (7) obtained in the present work is as accurate as the most accurate dimensionless models, the Petukhov equation (1) and the Gnielisky equation (2), allowing the former a wider range of application since it encompasses a larger region of validity, while the results obtained, despite slightly sacrificing the accuracy of the results by approximately 1%. However, the latter is justified considering that no known model has such a wide range of validity.

Figures 1 and 2 showed a graphical representation of the dependence between the hundredth part of the absolute mean error and the decimal logarithm of the product of the dimensionless numbers of Reynolds and Prandtl with the friction factor. In figure 1 it is provided for the interval $5 \leq Log\left(\mathrm{Re\,Pr}\, f\right) \leq 6{,}5$, while in the figure Are provided for the interval $3{,}5 \leq Log\ (Re\ Pr\ f) < 5$.

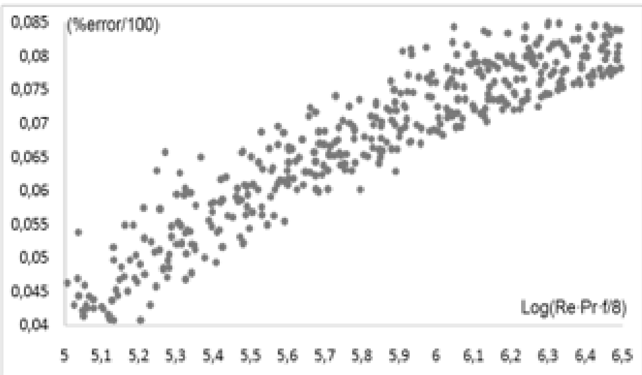

Figure 1. Graphical representation of absolute mean errors of the new model

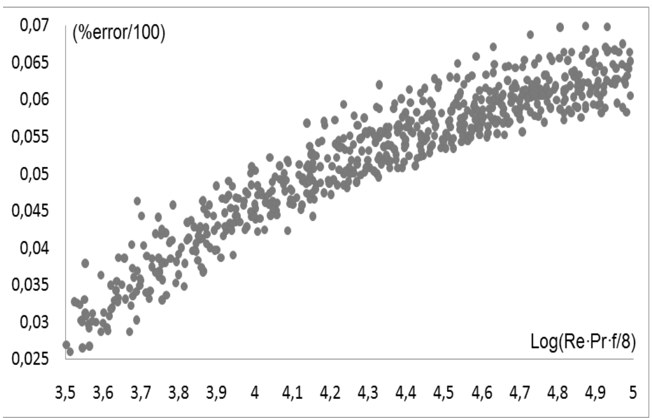

Figure 2. Graphical representations of absolute mean errors of the new model

4. CONCLUSIONS

A model has been obtained for the determination of the mean heat transfer coefficient in the turbulent regime through the interior of straight tubes, which has a slightly lower adjustment than the most precise dimensionless models, the Petukhov and Gnielinsky equations, However the model obtained has a wider range of application, covering almost double the values that the models that were taken as reference patterns, and that are also not covered by any known relation of calculation, reason why the use is recommended of the new expression in obtaining the values of the average coefficients of heat transfer by convection inside straight tubes through which turbulent flow circulates, either in transition state or total turbulence

This equation is given by expression (7) and responds to the following formulation:

$$Nu = \frac{\left(\mathrm{Re}_d - 10^D\right)\mathrm{Pr}}{A \times B^2 - C \times B\left(1 - \mathrm{Pr}^{2/3}\right)}\left(1 + \left(\frac{d}{l}\right)^{2/3}\right)\left(\frac{\mu_P}{\mu_M}\right)^N$$

Being fair to

$$2{,}3 \cdot 10^3 < \mathrm{Re} < 8{,}2 \cdot 10^6 \quad ; \qquad 0{,}5 \leq \mathrm{Pr} \leq 1{,}26 \cdot 10^4 \quad ;$$

$$0{,}025 \leq \left(\frac{\mu_P}{\mu_F}\right) \leq 42{,}2$$

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NOMENCLATURE

G	Mass flux, kg. $m^{-2}.s^{-1}$
Cp	Specific heat, J. $kg^{-1}.K^{-1}$
d	Inner equivalent tube diameter, m
g	gravitational acceleration, $m.s^{-2}$
Re	Reynolds number
Nu	Nusselt number for single-phase
Pr	Prandtl number
P	Fluid pressure, kg. $m^{-1}.s^{-2}$
T_P	Wall temperature, ^0C
N	Numbers of experimental points.
V	Fluid Velocity, $m.s^{-1}$
e	Equivalent grain size of rough

Greek symbols

α	Single-phase heat transfer coefficient, $kg.m^{-2}.s\text{-}3.K^{-1}$
μ	Dynamic viscosity, kg. $m^{-1}.s^{-1}$
μ_P	Dynamic viscosity at the wall mean temperature , kg. $m^{-1}.s^{-1}$
μ_F	Dynamic viscosity at the fluid mean temperature, kg. $m^{-1}{\cdot}s^{-1}$
λ	Fluid thermal conductivity, $W.m^{-1}$. K^{-1}
f	Darcy's friction factor
l	Duct's length, m

Subscripts

Eq.	Equation