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A numerical correlation development study for the determination of Nusselt numbers during boiling and condensation of R134a inside smooth and corrugated tubes ☆

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ABSTRACT

In this study, the closed form of artificial neural network method is used to have a reliable empirical correlation to estimate the measured Nusselt numbers of R134a flowing downward and horizontally inside smooth and corrugated copper tubes by means of some dimensionless numbers. R134a and water are used as working fluids flowing in the tube side and annular side of a double tube heat exchanger, respectively. The training sets have the experimental data of in-tube condensation and in-tube boiling tests including various mass fluxes and saturation temperatures of R134a. Inputs of the formula are the dimensionless numbers obtained from measured values of test section such as Froude number, Weber number, Bond number, Lockhart and Martinelli number, void fraction, the ratio of density to dynamic viscosity, liquid, vapor and equivalent Reynolds numbers, surface tension parameter and liquid Prandtl number, while the output of the formula is the experimental Nusselt numbers in the analysis. Nusselt numbers of R134a are modeled using closed form of multi-layer perceptron (MLP) method of artificial neural network (ANN). Analyses of the ANN method are accomplished by means of 1177 data points. The performance of the closed form of multi-layer perceptron (MLP) with three inputs and one hidden neuron architecture was found to be in good agreement, predicting the experimental Nusselt numbers with their deviations being within the range of ±30% for all tested conditions. Empirical correlations are proposed for both condensation and boiling flows separately. A single empirical correlation is found to be capable of predicting the experimental Nusselt numbers of both condensation and boiling flows together. Dependency of output of the ANNs from input values is also investigated in the paper. Vapor Reynolds number, equivalent Reynolds number, Weber number and Froude number are found to be the most affective parameters as a result of the dependency analyses.

1. Introduction

Heat exchangers using in-tube condensation have great significance in the refrigeration, automotive and process industries. Effective heat exchangers have been rapidly developed due to the demand for more compact systems, higher energy efficiency, lower material costs and other economic incentives. The surface area of heat exchangers has a directly significant effect on their heat-transfer performance. Improvements to make heat transfer equipment more energy-efficient would need to focus on miniaturization on the one hand and an astronomical increase in heat flux on the other. Normally, heat-transfer enhancement techniques necessarily reduce the thermal resistance in a conventional heat exchanger by promoting a higher convection heat-transfer coefficient in order to minimize the size of the heat exchanger. Recent numerical studies of authors on these subjects regarding the two-phase flows in the literature are summarized in the following paragraphs.

Dalkilic and Wongwises [1,2], Laohalertdecha et al. [3], and Balcilar et al. [4] reviewed the studies on in-tube condensation using smooth and enhanced tubes intensively since two-phase flow in tubes is the most challenging phenomenon in the heat exchanger systems. All effective possible research subjects of in-tube condensation were classified generally according to the tube orientation (horizontal, vertical, and inclined tubes) and tube geometry (smooth and enhanced tubes). Detailed information on the in-tube condensation studies of heat transfer, pressure drop, flow pattern, void fraction, and refrigerants in the literature were given. Their papers not only mention the new enhancement techniques of heat transfer, but also include some information on the new refrigerants, theoretical, numerical and empirical models in the literature.

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Nomenclature

Bo	Bond number
d	internal tube diameter, m
f	function
Fr	Froude number
G	mass flux, kg m^{-2} s^{-1}
j	superficial velocity
Pr	Prandtl number
R	ratio of density to dynamic viscosity
Re	Reynolds number
x	average vapor quality
We	Weber number
X_{tt}	Lockhart and Martinelli parameter

Greek Symbols

α	void fraction
ρ	density, kg m^{-3}
μ	dynamic viscosity, kg m^{-1} s^{-1}
σ	surface tension, N m^{-1}
Ψ	surface tension parameter

Subscripts

ANN	artificial neural network
eq	equivalent
exp	experiment
g	gas
h	hydraulic
l	liquid
TP	two-phase

Artificial intelligence methods such as genetic algorithms (GAs) and artificial neural networks (ANNs) modeling validated by the experimental work, have been gaining increased popularity in correlating two-phase flows in tubes. However, investigations into the prediction of in-tube condensation and evaporation's characteristics by means of artificial intelligence techniques are not sufficient in the literature. Authors of this paper have these publications on the determination of heat transfer characteristics of two-phase flows in-tubes numerically [5–10].

Improvements in condensation heat transfer in horizontal tubes have been the subject of significant concern in the design and operation of air conditioning and refrigeration systems. Performance of smooth tubes has been determined by many researchers with pure refrigerants as operating fluids. Generally, empirical methods have been offered to compute the condensation heat transfer coefficients in horizontal smooth-tubes. In the past, some researchers have studied several enhancement techniques, such as rough surfaces and twisted-tape inserts, while on the other hand, micro-fin and corrugated tubes have recently been used intensively because of their high condensation heat transfer performance and moderate pressure drop. Authors of this paper have these publications on the determination of two-phase heat transfer coefficient in smooth and enhanced tubes [11–22]. This paper is a continuation of the authors' previous works and includes all their previous works about condensation and boiling in tubes.

The leading aim of this study is to model the condensation and boiling in smooth and corrugated tubes in MATLAB with the methods of MLP and NLS, and then determine the most affected parameters and develop reliable correlations with several sets of basic heat transfer data [11,19–21] belonging to the condensation and boiling flow in smooth and corrugated tubes. The proposed correlations are believed to be useful in predicting the heat transfer characteristics of new smooth and corrugated tubes, without additional experiments, due to the use of reliable data from the authors' laboratory in King Mongkut's University of Technology Thonburi.

2. Experimental apparatus and method

Detailed descriptions of the experimental apparatuses and summary of test conditions in terms of flow type, refrigerant, mass flux, average pressure, inlet and outlet vapor qualities and number of data points belonging to the data for studying condensation and evaporation of R134a inside horizontal/vertical smooth and corrugated tubes can be found either in authors' previous publications and in Table 1 partly.

3. Calculation procedure for the analyses

3.1. Error analysis

The error analyses' calculation procedure for the average values of the experimental and calculated results of the two-phase pressure drops regarding with R square error, proportional error and mean square error (MSE) can be seen from authors' previous publications.

3.2. The generalized artificial neural networks (ANNs) model

The detailed information on the ANN analyses of the determination condensation heat transfer coefficient, pressure drop and correlation development can be seen from the authors' previous publications. It should be noted that the authors benefitted from either their own experimental database or their database of independent laboratories in these publications.

Table 1
Experimental parameters and operating conditions.

Data set Specifications	Data set 1 [11]	Data set 2 [19]	Data set 3 [20]	Data set 4 [21]
Phase change type	Condensation	Condensation	Boiling	Boiling
Refrigerant type	R134a	R134a	R134a	R134a
Tube type	Smooth	Smooth and 5 different corrugated tubes	Smooth and 5 different corrugated tubes	Smooth and 5 different corrugated tubes
Tube orientation	Vertical	Horizontal	Vertical	Horizontal
Inner diameter (m)	0.0081	0.0081	0.0087	0.0081
Tube length (m)	0.5	2.5	0.85	2.5
Mass flux (kg m^{-2} s^{-1})	260, 300, 340, 400, 455, 515	200, 300, 400, 500, 600, 700	200, 300, 400	300, 400, 500
Saturation pressure (bar)	10, 12	10, 11.3, 12.7	4,5, 5.7	4,5, 5.7
x_{avg}	0.7–0.96	0.07–0.82	0.14–0.86	0.09–0.81
Number of data points	368	280	302	227

Table 2
Proposed correlations and their error rates.

Eq. number	Proposed correlation	Data set	MSE	RMSE	R^2	Data number
1	$Nu = \frac{b_1}{1+\exp\left[b_2\psi+b_3\frac{Re_{eq}}{10000}+b_4Pr_l+b_5\right]}$ $b_1 = 2207.661, b_2 = 6.857,$ $b_3 = -0.171, b_4 = -0.37, b_5 = 3.213$	All data	6140	78.34	0.8	1177
2	$Nu = \frac{b_1}{1+\exp\left[b_2\psi+b_3\frac{Re_{el}}{10000}+b_4\frac{Re_g}{10000}+b_5\right]} + b_6$ $b_1 = -1385.293, b_2 = -17.339, b_3 = 0.641,$ $b_4 = 0.108, b_5 = -2.656, b_6 = 1614.92$	1–3	6063.5	77.9	0.84	670
3	$Nu = \frac{100000}{1+\exp\left[b_1\frac{Re_{el}}{10000}+b_2\frac{Re_g}{10000}+b_3\frac{Re_{eq}}{10000}+b_4\right]}$ $b_1 = -4.606, b_2 = -1.73, b_3 = 4.615,$ $b_4 = 5.827$	2–4	4374.6	66.14	0.71	507
4	$Nu = \frac{100000}{1+\exp\left[b_1Bo+b_2\psi+b_3\frac{Re_{eq}}{10000}+b_4\right]}$ $b_1 = 0.014, b_2 = 3.958, b_3 = -0.118,$ $b_4 = 3.112$	1–2	7946.6	89.14	0.8	648
5	$Nu = \frac{22650}{1+\exp\left[b_1Bo+b_2\frac{Re_g}{100000}+b_3\frac{Re_{eq}}{10000}+b_4\right]} + b_5$ $b_1 = -0.083, b_2 = -0.292, b_3 = -1.749,$ $b_4 = 7.774, b_5 = 228.98$	3–4	2322.2	48.19	0.77	529
6	$Nu = \frac{2286}{1+\exp\left[b_1Bo+b_2\frac{Re_g}{100000}+b_3Pr_l+b_4\right]} + 263$ $b_1 = -6.23, b_2 = -7.91, b_3 = -138.177,$ $b_4 = 604.191$	1	11304	106.32	0.68	368
7	$Nu = \frac{-466}{1+\exp[b_1Fr+b_2X_{tt}+b_3]} + 741$ $b_1 = 0.003, b_2 = -1.109, b_3 = -1.098$	2	4279	65.4	0.58	280
8	$Nu = \frac{b_1}{1+\exp\left[b_2Bo+b_3\frac{Re_{eq}}{10000}+b_4\right]}$ $b_1 = 645.682, b_2 = -0.065, b_3 = -0.171,$ $b_4 = 1.667$	3	382	19.5	0.75	302
9	$Nu = \frac{b_1}{1+\exp\left[b_2Bo+b_3\frac{Re_{eq}}{10000}+b_4Pr_l\right]}$ $b_1 = 1790.746, b_2 = -0.056, b_3 = -0.212,$ $b_4 = 0.944$	4	2421	49.2	0.88	227

3.3. The closed form of MLP

The success of the modeling experimental data with MLP has been reported many times by the researchers. But the worst part of this method is the mathematical expression of the relationship between input and output grows by growing architecture of MLP. Because of the relationship between inputs and outputs is not showing as a simple equation, this method is called by the researchers as black box. The success of correlation decreases when the model architecture is quite small, but this time, the closed form of the model is too simplified, and it can be shown as a simple equation. For that reason, in this study, the closed form of MLP with 3-1-1 architecture is used. In this model the transfer function of hidden layer is considered to be tansig function. According to this consideration the output of hidden layer is written as Eq. (1).

$$O_h = \frac{1}{1+\exp\left[w_1^1 \cdot I_1 + w_2^1 I_2 + w_3^1 I_3 + b_1\right]} \tag{1}$$

Because of the transfer function of output layer is considered to be linear function, the output of the model, in other word, the closed form of model is written as Eq. (2).

$$O = \frac{w_1^2}{1+\exp\left[w_1^1 \cdot I_1 + w_2^1 I_2 + w_3^1 I_3 + b_1\right]} + b_2 \tag{2}$$

3.4. The non-linear least square (NLS) algorithm

The non-linear least square (NLS) method allows the user to determine the most optimal non-linear function coefficients in order to fit data collected from an experimental environment to a non-linear function (non-linear curve fitting). This method tries to minimize the mean square error, beginning from the first estimated values determined by the user. Since it advances step by step through optimizing this point, it finds the local minimum and not the global minimum by starting from this initial point. The method is tested by starting from different initial points, and thus the global minimum value of model is determined.

3.5. Correlation development for the two-phase pressure drop

There have been a number of studies on the in-tube condensation and evaporation pressure drops of smooth and enhanced tubes in the literature. Generally, empirical methods have been used to compute

Table 3
The most predictive input parameters according to the error rates.

Inputs											Input number	Data Set	Output
Fr	We	Bo	X_{tt}	α	ψ	Re_l	Re_g	Re_{eq}	R	Pr_l			$R^2 - Nu$ (%)
0	0	0	0	0	0	0	1	0	0	0	1	All	0.891
0	0	1	0	0	0	0	1	0	0	0	2	All	0.896
0	0	0	0	0	1	0	0	1	0	1	3	All	0.897
0	0	0	0	0	0	0	1	0	0	0	1	1–3	0.914
0	0	0	0	0	0	0	1	0	1	0	2	1–3	0.916
0	0	0	0	0	1	1	1	0	0	0	3	1–3	0.917
1	0	0	0	0	0	0	0	0	0	0	1	2–4	0.765
1	0	0	0	0	0	0	0	0	10	0	2	2–4	0.806
0	0	0	0	0	0	1	1	1	0	0	3	2–4	0.843
0	0	0	0	0	0	0	1	0	0	0	1	1–2	0.883
0	0	0	0	0	1	0	0	1	0	0	2	1–2	0.89
0	0	1	0	0	1	0	0	1	0	0	3	1–2	0.894
0	0	0	0	0	0	0	0	1	0	0	1	3–4	0.855
0	0	1	0	0	0	0	0	1	0	0	2	3–4	0.879
0	0	1	0	0	0	0	1	1	0	0	3	3–4	0.881

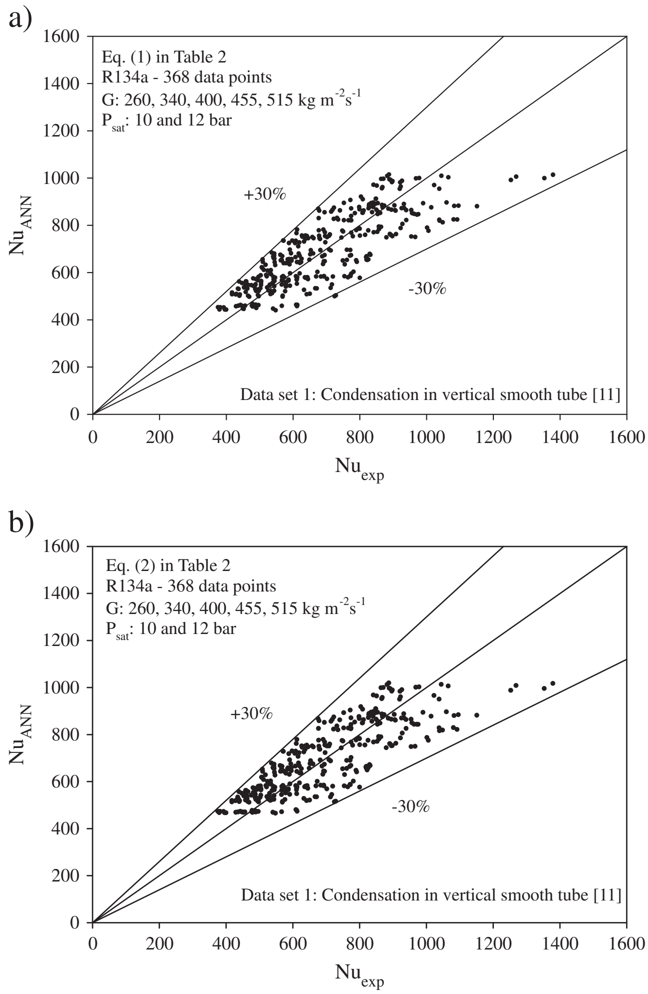

Fig. 1. Performance comparison of Eq. (1) (a) and Eq. (2) (b) for the data set 1.

the Nusselt numbers and convective heat transfer coefficients in tubes. As a result, Eq. (3) is formed to predict the Nusselt number of evaporation and condensation in terms of the above explanations as follows

$$Nu = \frac{b_1}{1 + \exp\left[b_2\psi + b_3\frac{Re_{eq}}{10000} + b_4 Pr_l + b_5\right]} \tag{3}$$

where the coefficients from b_1 to b_5 are the constants. It should be noted that detailed information on the developed correlations can be seen in Table 2.

The inputs of model have the following dimensionless numbers to determine their effects on the Nusselt number selected as the output of the analyses. Table 3 shows the significance of these input parameters below considering their error values of R^2.

The all liquid equivalent Re number is determined from:

$$Re_{eq} = \frac{G_{eq} d_h}{\mu_l} \tag{4}$$

and equivalent liquid mass flux and the ratio of density to dynamic viscosity are defined as:

$$G_{eq} = G\left((1-x) + x\left(\frac{\rho_l}{\rho_g}\right)^{0,5}\right) \tag{5}$$

$$R = \frac{\rho_l \mu_l}{\rho_g \mu_g} \tag{6}$$

and Bond number and the Froude number are defined respectively as:

$$Bo = g\left(\rho_l - \rho_g\right)\left(\frac{(d_h/2)^2}{\sigma}\right) \tag{7}$$

$$Fr = \frac{G^2}{g d_h \rho_{TP}^2} \tag{8}$$

where the two-phase density and the Lockhart and Martinelli parameter is determined from:

$$\rho_{TP} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{9}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\mu_g}{\mu_l}\right)^{0.1}\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{10}$$

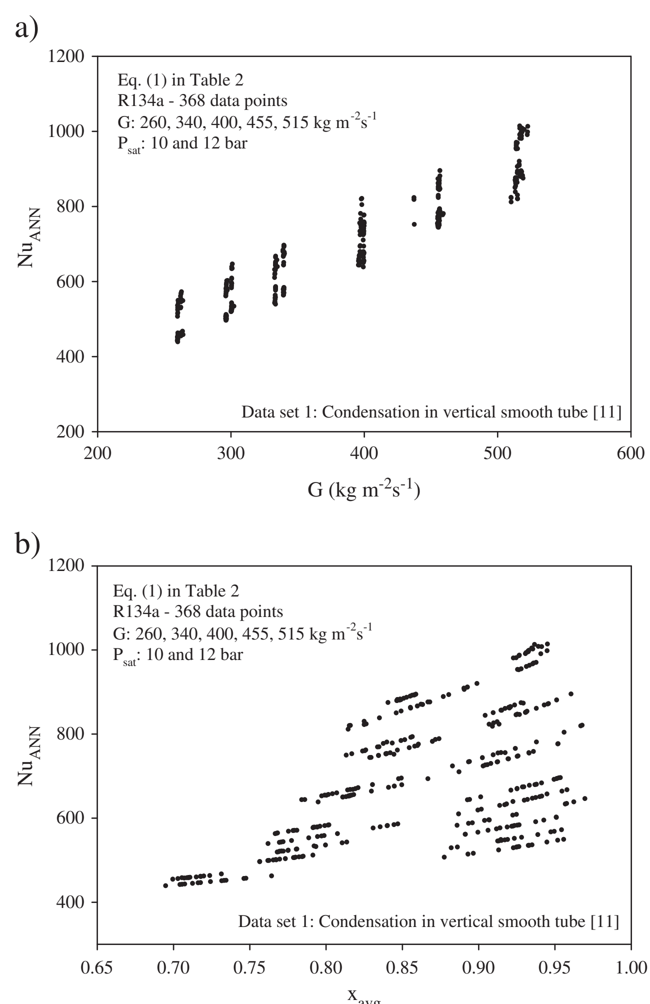

Fig. 2. Alteration of obtained Nusselt numbers with mass flux (a) and average vapor quality (b) for data set 1.

and the all liquid Reynolds number and all gas Reynolds number equations can be expressed as:

$$Re_l = \frac{Gd_h}{\mu_l} \tag{11}$$

$$Re_g = \frac{Gd_h}{\mu_g} \tag{12}$$

and the void fraction, α, can be determined from Butterworth's correlation as follows:

$$\alpha = \frac{1}{1 + 0.28\left(\frac{1-x}{x}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}} \tag{13}$$

and Weber number, We, is used as:

$$We = \frac{G^2 d_h}{\sigma \rho_{TP}} \tag{14}$$

and surface tension parameter, ψ, and the liquid superficial velocity, j_l, are calculated respectively.

$$\psi = \frac{j_l \mu_l}{\sigma} \tag{15}$$

$$j_l = \frac{G(1-x)}{\rho_l(1-\alpha)} \tag{16}$$

4. Results and discussion

The following paragraphs numerically present the discussion of calculated Nusselt numbers of condensation and boiling flows of R134a using the database of authors' previous studies [11,19–21] in horizontal/vertical smooth and corrugated tubes. It should be noted that detailed explanations and some additional figures and tables containing different experimental parameters related to their studies on the heat transfer characteristics can be seen in the applied reference databases [11,19–21], which demonstrate the accuracy of the experiments. A discussion of the results follows.

There are one-type of closed form formula in the paper. It is developed for the calculation of the coefficients in correlations in Table 2 using the experimental databases in Table 1. The inputs of closed form are selected in the set of Froude number, Weber number, Bond number, Lockhart and Martinelli number, void fraction, the ratio of density to dynamic viscosity, liquid, vapor and equivalent Reynolds numbers, surface tension parameter and liquid Prandtl number, while the output of the closed form is the experimental Nusselt numbers in the analysis. Four-fold cross validation was used

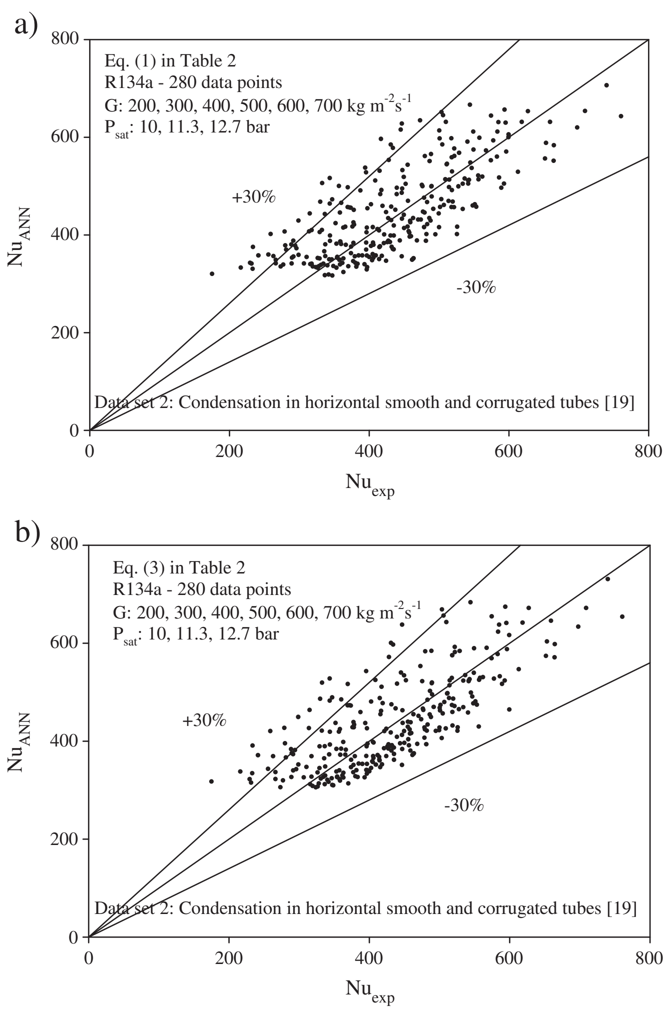

Fig. 3. Performance comparison of Eq. (1) (a) and Eq. (3) (b) for the data set 2.

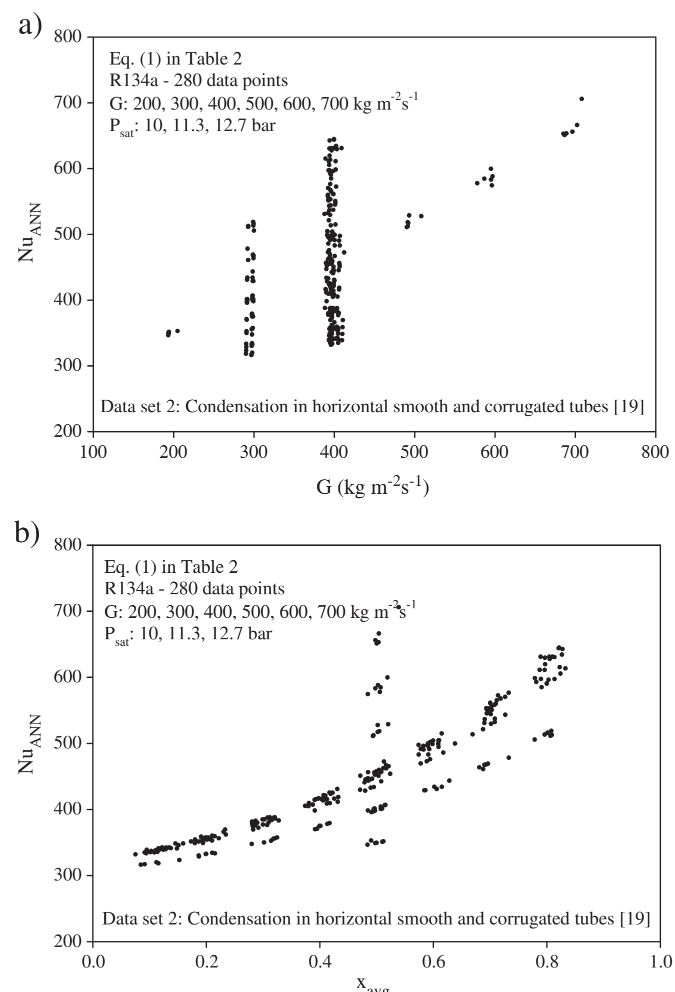

Fig. 4. Alteration of obtained Nusselt numbers with mass flux (a) and average vapor quality (b) for data set 2.

for regression analysis. It means that 1177 data points (all data of boiling and condensation in smooth and corrugated tubes) were divided by 4 sets randomly and one of the sets selected for the test process, and the rest of them (3 sets) were selected for the training process. These processes were continued until there were no untested data sets. Four different data sets of researchers [11,19–21] are defined in Table 1 and used for all analyses. It should be noted that although various architectures were tested for elimination, only the typical one was used in the paper due to limited space.

Table 1 shows the operating conditions of the database. 1177 data points were used in the analyses. 648 of them belong to in tube flow of condensation of vertical and horizontal orientations whereas 529 of them belong in tube flow of boiling of vertical and horizontal orientations. There were 5 different corrugated tubes and a smooth tube having 8 mm i.d. tested in the experiments. Mass fluxes and vapor qualities had a wide range for the accuracy of the developed correlations.

Table 2 includes 9 different developed correlations for each dataset or combination of them separately. Their R^2 values show their success and reliability. Eq. (1) in Table 2 has the most importance among others in the paper. It can predict all data including condensation/boiling in smooth/corrugated horizontal/vertical tubes at the same time with an acceptable accuracy as shown in all figures. The difference between the R^2 results is due to the hardness of generalization in the two-phase flow.

Table 3 illustrates the dependency of the output parameter from the input ones, in other words, these tables imply the most important affective dimensionless number on the prediction of the Nusselt number. It is possible from this table to determine the first 3 most affective parameters of databases separately. From this table, it is possible to reveal that vapor Reynolds number, equivalent Reynolds number and Weber number have the most influence on the Nusselt number considering all databases with their R^2 values over 0.8. Moreover, Froude number has also some importance apart from other input parameters. In this analysis, when the input parameter number is one in all databases, vapor Reynolds number seems to be dominant on the prediction of the Nusselt number with the R^2 value of 0.891. When there are 2 known input parameters, vapor Reynolds number and Bond number have the R^2 value of 0.896. When there are 3 known input parameters, vapor Reynolds number, Bond number and surface tension parameter have the R^2 value of 0.897. Datasets 1–3 refer to condensation and boiling datasets in vertical smooth and corrugated tubes, datasets 2–4 refer to condensation in horizontal tubes and boiling in vertical smooth and corrugated tubes, datasets 1–2 refer to condensation in horizontal and vertical smooth and corrugated tubes, datasets 3–4 refer to boiling in horizontal and vertical smooth and corrugated tubes as they can be realized from Table 1. These tables show that the accuracy of the estimated output value by means of input values increases along an increasing number of proper input parameters. In addition, they show the existence of less important input parameters on the prediction of the Nusselt number. It should be noted that it is possible to derive more results from these tables for each database specifically.

In this paper, an intensive concentration has been focused on the determination of the Nusselt numbers using all datasets by means of Eq. (1) in Table 2. The predictability (a) and performance comparison with other developed correlations (b) can be seen from Figs. 1, 3, 5 and 7. As it can be seen from these figures, majority of data points fall

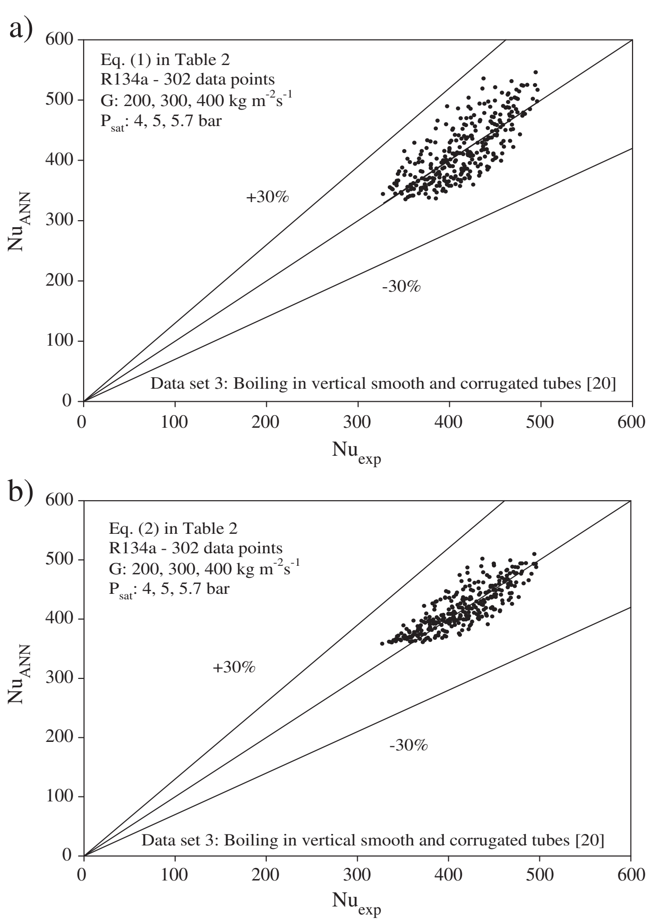

Fig. 5. Performance comparison of Eq. (1) (a) and Eq. (2) (b) for the data set 3.

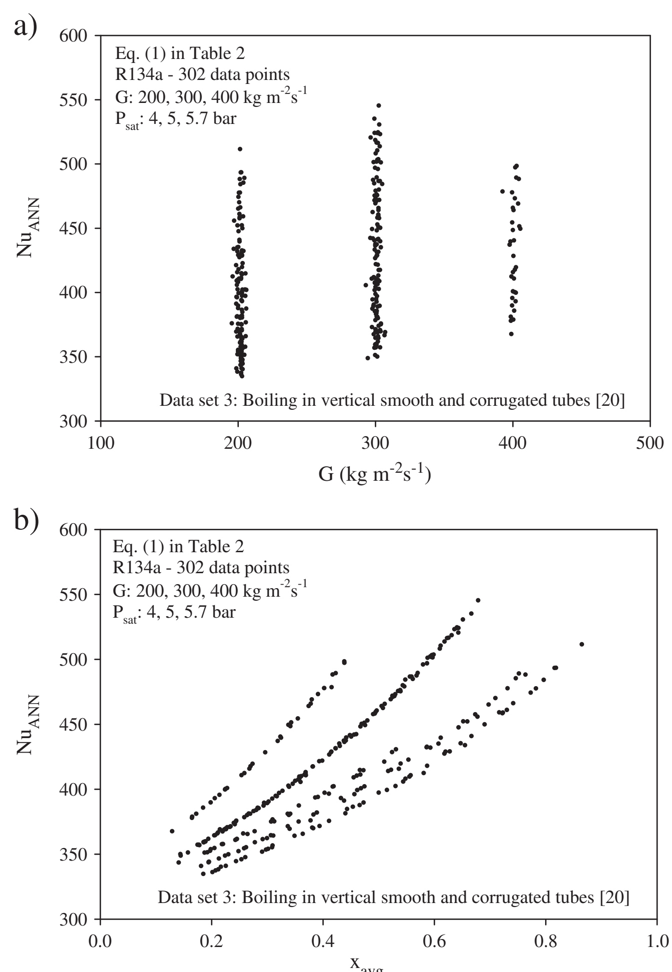

Fig. 6. Alteration of obtained Nusselt numbers with mass flux (a) and average vapor quality (b) for data set 3.

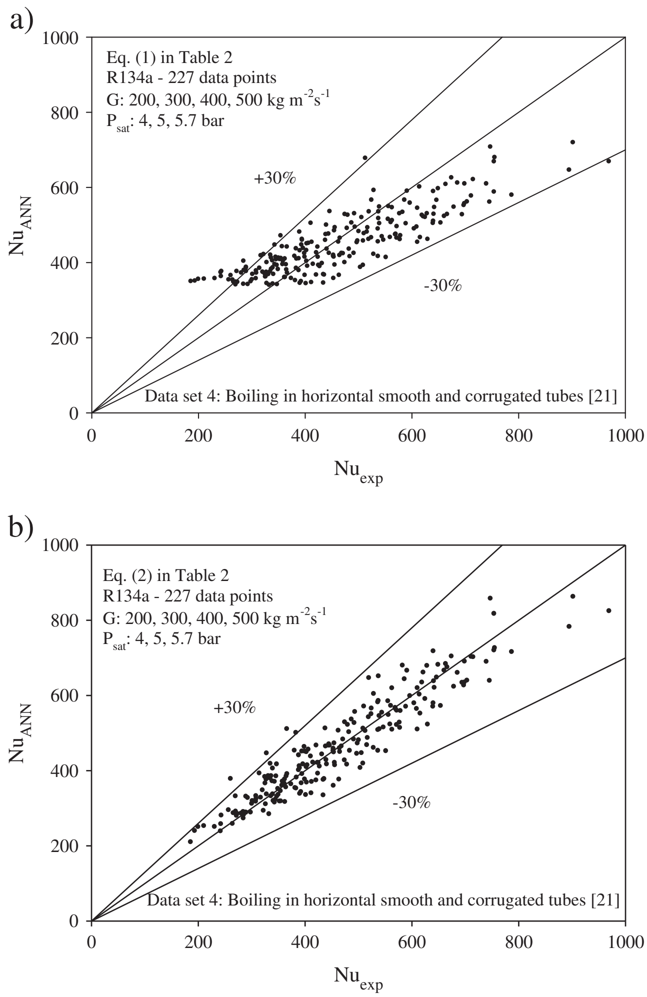

Fig. 7. Performance comparison of Eq. (1) (a) and Eq. (2) (b) for the data set 4.

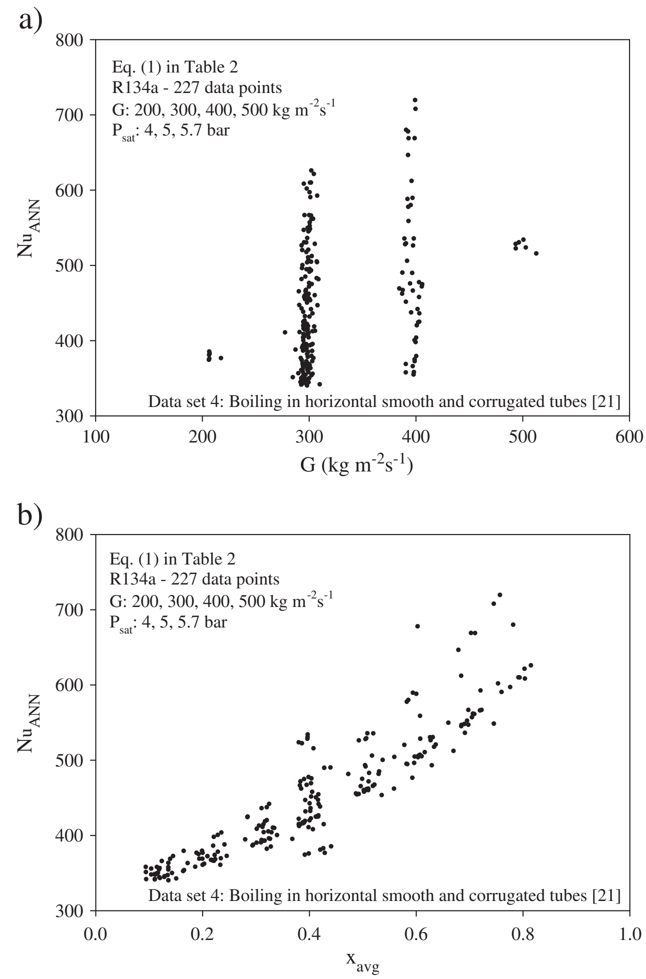

Fig. 8. Alteration of obtained Nusselt numbers with mass flux (a) and average vapor quality (b) for data set 4.

under the $\pm 30\%$ deviation bands for all proposed correlations. Figs. 2, 4, 6 and 8 show the proposed correlations' results meaningfulness considering the trends in the alterations of the obtained Nusselt numbers and mass fluxes (a) and average vapor qualities (b). As expectedly, Nusselt numbers increases with increasing mass fluxes and vapor qualities in all datasets.

5. Conclusion

Numerical analyses have been performed to determine the Nusselt numbers and to develop reliable correlations of condensation and boiling in smooth and corrugated tubes by means of computational numerical techniques. In order to derive reliable correlations, the authors' experimental databases in the literature [11, 19–21] are used in the analyses. This paper reports that although there are numerous studies on the determination of two-phase Nusselt numbers in tubes, application of artificial neural networks (ANN) together with non-linear least squares (NLS) to the in-tube boiling and condensation for the aim of correlation development does not exist in the literature. For that reason, the content of this study is expected to fill this gap in the literature.

Not only this paper proposes some correlations for boiling and condensation datasets but also it enables researchers to predict both condensation and boiling flows in smooth/corrugated horizontal/vertical tubes by means of a single correlation with a reasonable deviation.

Dependency of output of the ANNs closed form from input values is investigated in the paper. Vapor Reynolds number, equivalent Reynolds number, Weber number and Froude number are found to be the most affective parameters as a result of the dependency analyses.

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