

# Development of Generalized ANFIS Model for Flow Boiling of Refrigerants on Plain Tube Bundles

Abhilas Swain, and Mihir Kumar Das

**Abstract**—The present article concentrates on the development of a generalized ANFIS model to determine the flow boiling heat transfer coefficient on tube bundles specifically for refrigerants. The data being gathered for the present work comprises of the flow boiling experimental data for five refrigerants named R113, R123, R134, R507a and R236fa. Two widely used semi-empirical correlations proposed by Cornwell and Houston and Shah are tested with these refrigerant data for comparison with ANFIS model. These correlations fail to predict the data in all the regimes within a tolerable error of  $\pm 20\%$ . The separate ANFIS models developed by training and validation through the experimental data for each liquid are able to predict the same liquid data within  $\pm 5\%$ . Then a generalized model is developed for all the five refrigerants. The non-dimensional terms such as Boiling number, Reynolds Number and reduced pressure and the molecular mass are taken as input and the heat transfer coefficients are predicted as output. The structure of the network is optimized to get the best model. The final model is able to predict all the five refrigerant data within  $\pm 20\%$  irrespective of regimes of flow boiling heat transfer.

**Index Terms**—Boiling heat transfer, ANFIS, Tube Bundle, Shell and Tube heat exchanger, General correlation.

## I. INTRODUCTION

The cross flow across tube bundle with boiling heat transfer as applied in the two phase shell and tube heat exchangers is an interesting and challenging area for researchers because of its wide application in the process and chemical industries. The determination of heat transfer coefficient is the vital part in the designing of efficient and compact two phase shell and tube heat exchanger with shell side boiling. Literatures reveal that different researchers have studied the boiling over tube bundles to analyze different aspects to augment the heat transfer process keeping in view the industrial applications and the review of recent research works can be found in Swain and Das [1]. The process of flow boiling outside tube bundles is very much complicated because of various influencing factors like bundle geometry, tube spacing, mass flux, pressure, heat flux, surface conditions and thermo-physical properties of the fluid. The different researchers investigate the effect of these different factors and still there are unveiled theories in boiling and nucleation process. The boiling heat transfer over tube bundle is so much complicated that, in spite of many correlations available, any one correlation fails to predict the other liquid-surface data within a tolerable range of  $\pm 20\%$ .

Manuscript received September 29, 2014.

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Latest literatures reveal that ANFIS is establishing itself as a strong tool to model complex problems replacing the conventional process of development of empirical correlations. Following investigations are carried out in the last two years in the area of application of ANFIS in modeling different heat transfer and thermal engineering problems. Razei et al. [2] applied the ANFIS technique to model the free convection in a partitioned air cavity in which the average Nusselt number over the heater wall is predicted as output taking the Rayleigh number and partition angle taking input. Beigzadeh and Rahimi [3] modeled the hydrostatics and fluid flow characteristics in helically coiled tubes to predict the Nusselt number and friction factor. Tahseen et al. [4] applied ANFIS to predict the Nusselt number and pressure drop in convection over in-line flattened tube bundles. The ANFIS model is able to predict the Nusselt Number and Dimensionless Pressure drop within  $\pm 5\%$ . Hosoz et al. [5] applied the ANFIS to model the performance and emission criteria of a diesel engine running with diesel fuel and biodiesel blends.

The ANFIS is implemented in the boiling area such as for prediction of critical heat flux by Gyun na[6] and Zaferanlouei et al. [7] and for prediction of heat transfer coefficient in pool boiling by Das and Kishore [8]. Therefore, use of ANFIS seems to be a promising method in prediction of flow boiling heat transfer coefficient which in turn is essential for compact and effective design of two phase shell and tube heat exchanger.

The present work is an attempt to create a generalized model using artificial intelligence technique. The required input parameters for generalized model, such as liquid Reynolds number, Reduced Pressure, molecular mass and boiling number are determined from the raw data taking the other properties of the fluid at the saturation temperature. The ANFIS model is trained with these input variables and boiling heat transfer coefficient as output. The structure or the numbers of fuzzy rules are optimized to get the best performing model. The correlation coefficients, mean relative error, mean square error and  $R^2$  values show characteristics of a good model.

## II. DATA GATHERING FOR TRAINING AND VALIDATION

The first step in the modelling process is to gather the data or system characteristics from the experimental setup. To form a generalized ANFIS model for boiling of saturated refrigerants over tube bundles, five liquids are selected. The refrigerants considered for present investigation are R113, R123, R134, R507a and R236fa. The details of the literatures from which data are collected are presented in the Table 1.

TABLE I: LITERATURES CONSIDERED FOR THE DATA OF SATURATED BOILING OF LIQUIDS OVER TUBE BUNDLES.

Sl. No	Authors	Liquids	Tube Bundle pitch and arrangement
1	Burnside and Sire [9]	R113	1.33
2	Gregory and Eckles[10]	R123	1.167
3	Robinson and Thome[11]	R134a, R507a	1.53
4	Rooyen and Thome[12]	R236fa	1.167

The variables are modified from the raw data to the stated input variables according to the following equations. For generalization of the model it is necessary to the non-dimensionalise the data.

The pressure is converted to non-dimensional form reduced pressure

$$P_r = P / P_{crit} \quad (1)$$

Boiling Number is given by following equation

$$Bo = q / \dot{m} h_{fg} \quad (2)$$

Then 75% of the data are considered for training and the rest are taken up for validation. The ANFIS built-in commands and options available in MATLAB software are used to create and train the network.

### III. VERIFICATION OF OTHER CORRELATIONS

To establish the ANFIS model it is necessary to compare the performance of the ANFIS with the other widely used conventional correlations. The data collected from the literature are first subjected to prediction by these conventional correlations. The Shah [13] model is a very recent model, developed considering data of various refrigerants, some hydrocarbons and water. The Shah [13] correlation prescribes different method of determination of HTC for different regimes distinguished by boiling intensity parameter defined as follows.

$$Y_{IB} = F_{pb} BoFr^{0.3} \quad (3)$$

TABLE II: HEAT TRANSFER REGIMES ACCORDING TO BOILING INTENSITY PARAMETER

Regime	Range of parameter	Mod of heat transfer	Dominating effect
Intense boiling regime	$Y_{IB} > 0.0008$	Nucleate boiling	Heat flux
Convective boiling regime	$0.00021 \leq Y_{IB} \leq 0.008$	Nucleate boiling and convection	Heat flux and mass velocity
Convective regime	$0.00021 \leq Y_{IB}$	Convection Process	Mass velocity and vapor quality

$$\text{Regime I : Intense boiling regime} \quad h_{cb} = F_{pb} h_{cooper} \quad (4)$$

$$\text{Regime II : Convective boiling regime} \quad \phi = \phi_o, \quad \phi = h_{cb} / h_f \quad (5)$$

$$\text{Regime III : Convective regime} \quad \phi = 2.3 / Z^{0.8} Fr^{0.22} \quad (6)$$

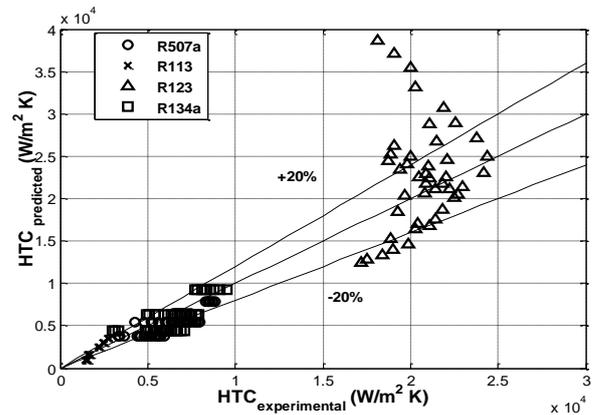


Fig. 1. Comparison of experimental value of HTC with those predicted from equations (2, 3, and 4) for flow boiling of R507a, R113, R123 and R134a on tube bundles.

The Shah model[13] prescribes to use the Coopers correlation for predicting the boiling heat transfer coefficient in for some range of values of boiling intensity parameter which corresponds to nucleate boiling regime. However, the cooper correlation has no term related to mass flux in the correlation. Therefore, for a particular value of heat flux, we have one heat transfer coefficient value for any mass flux range. The Shah [13] correlation is able to predict most of the data within  $\pm 20\%$  of the experimental value. However, the constant for material needs to be changed for different liquid surface combination to predict it within acceptable limit.

The Shah correlation is able to predict most of the data within an error of  $\pm 20\%$ . Figure shows the experimental data of R123 of Gregory and Eckles [10] are predicted with the shah correlation. In the reported data the results are represented for average vapour quality 50-60%. Thus for the calculation the vapour quality is taken to be 0.55. Thus some of the data may be deviating from the actual data due to this reason. Otherwise, most of the predicted data lies within the  $\pm 20\%$  of the experimental data. The constant for the material is upgraded to a value of 6.2 for this purpose. The tubes were enhanced tubes for which the constant for the material is required to taken a higher value.

The data of Gregory and Eckles [10] include the boiling of R123 on enhanced Trubo-II tube bundles. The Cornwell and Houston correlation [14] was formed from the data of boiling of liquids mostly refrigerants on plain tube bundle. However, in case of Gregory and Eckles[10] due to the enhanced surface the magnitude of heat transfer coefficient is higher and it is not at all predictable form the original correlation as there is no term accounting for type of surface.

The Cornwell and Houston [14] correlation is basically for the nucleate boiling regime. The nucleate boiling heat transfer coefficient is magnified by the liquid Reynolds number to determine the flow boiling heat transfer coefficient. The Cornwell and Houston [14] expression is given by the following expression.

$$Nu_{cb} = Nu_{nb} Re_l \quad (6)$$

$$\text{Where } Nu_{nb} = 9.7 P_{crit}^{0.5} F(P) Re_b^{0.67} Pr^{0.4} \text{ and}$$

$$Re_b = qD / \mu_l h_{fg} \quad (7)$$

Some of the predicted data are inside and some are outside of the  $\pm 20\%$  of the experimental value. As the correlation is

primarily meant for the nucleate boiling regime, it is going to deviate largely from the experimental data in the convective boiling regime. Also there is no term to account for the surface quality for which the predicting capability is hampered.

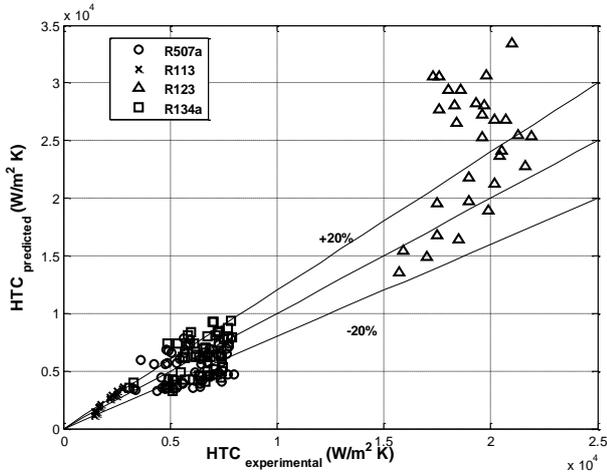


Fig. 2. Comparison of experimental value of HTC with those predicted from equations (6 and 7) for flow boiling of R507a, R113, R123 and R134a on tube bundles.

IV. ANFIS MODELLING OF INDIVIDUAL MODELS

The data taken for the modeling work are all experimental data. The boiling heat transfer coefficients at various heat flux, mass flux and pressure values are taken from the open literature. The heat flux and mass flux data are converted to Boiling number and the pressure values are converted to the reduced pressure value for reducing the number of inputs. The output is same the heat transfer coefficients. The general architecture of the ANFIS model taken is shown in Figure 3.

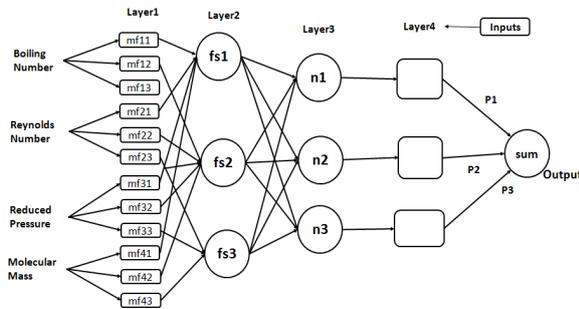


Fig. 3. Structure of the ANFIS model

The different ANFIS model created for the different refrigerant data taking the boiling number and the reduced pressure as input and predicting the heat transfer coefficient as output. The individual models for the respective refrigerant are able to predict the heat transfer coefficient within an error of  $\pm 5\%$ .

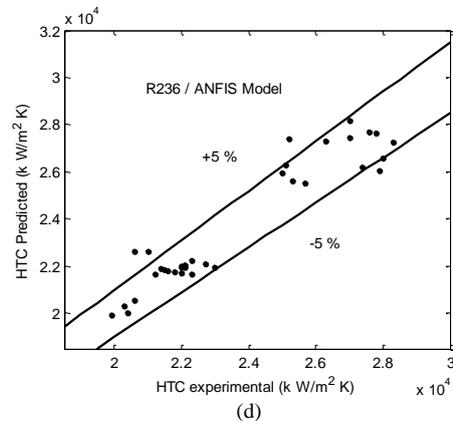
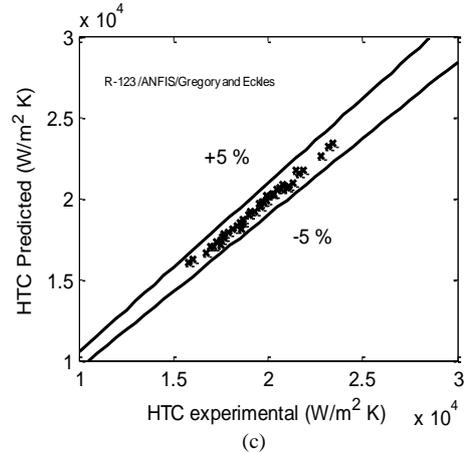
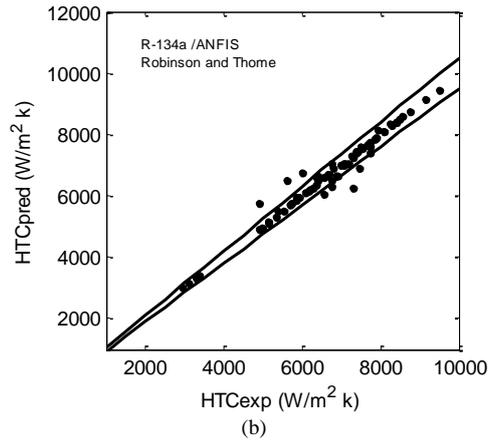
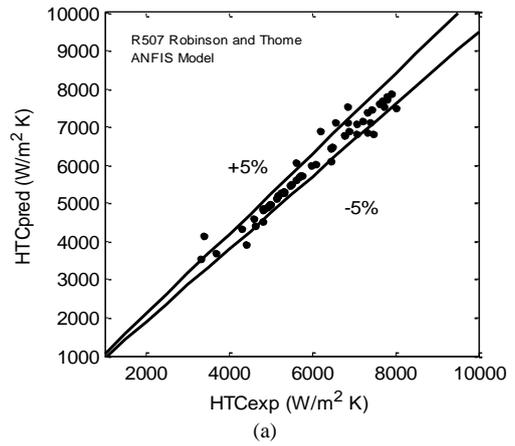


Fig. 4. Comparison of the HTC predicted from ANFIS with experimental for (a) R507a (b)R134a (c) R123 (d)R236fa

Figure 4 shows the comparison of the predicted and experimental heat transfer coefficient in flow boiling for

different refrigerants. As the data set belongs to the same liquid in a particular range of parameters the model formed is accurate in predicting the heat transfer coefficients.

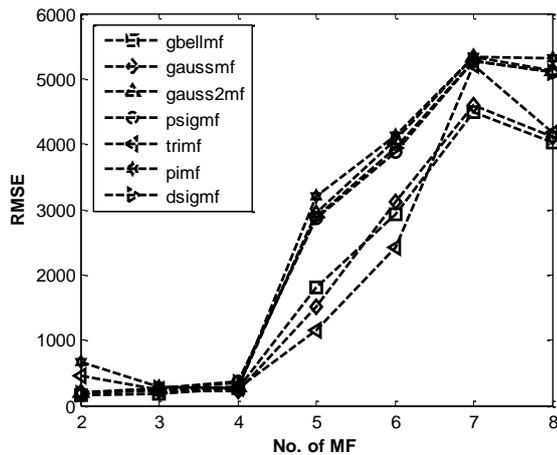


Fig. 5. variation of root mean square error with number of membership functions for various types of membership functions

To find out the best final ANFIS model, the models are tested varying the same kind and number of membership function. Figure 5 shows the variation of the RMSE with the number of membership functions for various types of membership functions. The RMSE for the three number of membership function is the lowest and as generalised Bell type membership functions are considered for its property [8]. Therefore, for the final model the Bell type membership function is taken with three numbers.

#### V. DEVELOPMENT OF GENERALIZED ANFIS MODEL

The individual ANFIS models created for each refrigerant are capable of predicting the experimental data with a good accuracy because they belong to the same pattern and the same liquid. However, a lot difficulty arises in making a single model capable of predicting the experimental data of all five refrigerants with reasonable accuracy. The heat flux and mass flux are converted to the boiling number as expressed in the equation 2. The molecular mass and liquid Reynolds numbers of the liquids are also considered for the representation of the liquid properties. The incorporation of the molecular mass into the model is inspired by the Coopers correlation, which is widely used due to its capability in predicting the boiling heat transfer coefficient in the nucleate boiling heat transfer regime. Figure 6 shows the comparison between the predicted and the experimental data for all the liquid with the default architecture available in the MATLAB. The default architecture means all the links between the first layer and the second layer are present. By forcibly putting the value associated with the link to zero we can remove the particular link.

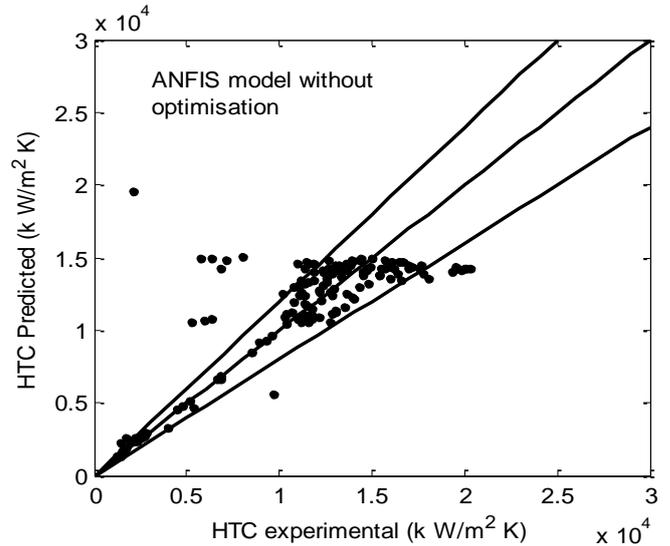


Fig. 6. Comparison of HTC predicted (ANFIS optimised) with experimental for all the five refrigerants (R507a,R123,R113,R134a and R236fa)

After taking all these parameters (Boiling Number, Reduced Pressure, Molecular mass and Liquid, Reynolds) as input variables the model created and trained is not able to predict the heat transfer coefficient. The predicted data from this model deviate largely from the experimental data in the higher heat transfer coefficient range.

Then to make the model better the architecture of the network has to be changed suiting to the data set. The number and combinations of the antecedents or the links between the first layer and the second layer are changed by applying different combinations. Different sets of combinations of numbers 1-16 are created and the corresponding links are disabled. The different combinations are the set of numbers (having number of elements 8, 10 and 12) ranging from 1-16 positive integers. Each combination is then tested to determine the  $R^2$  value. Then the combination having the highest  $R^2$  value is chosen as the best model. Figure 7 shows the prediction of the best model among the models tested for removing the connecting links as per the combinations produced. The statistical performance parameters for the different models are presented in Table 3.

TABLE III: STATISTICAL PERFORMANCE PARAMETERS OF THE MODELS

Models	R Square	RMSE	MSE
General Model without optimisation	0.9235	189.41	28636.683
General Model with optimisation	0.9563	186.73	28422.549

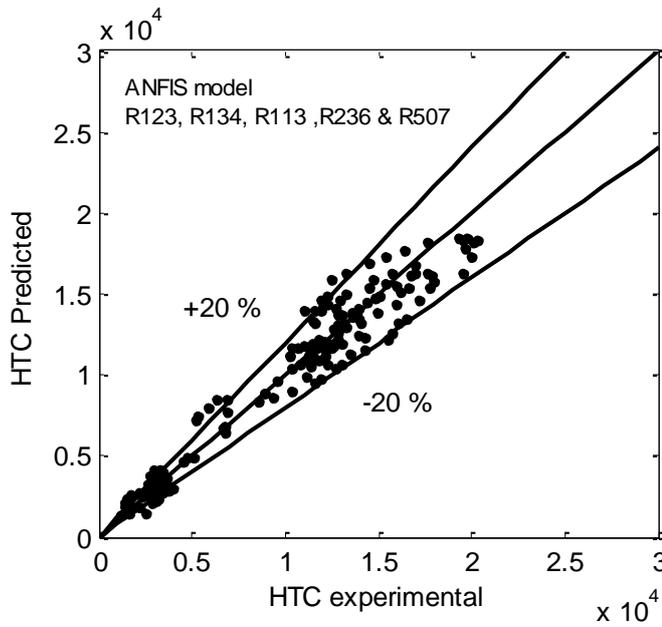


Fig. 7. Comparison of HTC predicted (ANFIS optiised) with experimental for all the five refrigerants (R507a,R123,R113,R134a and R236fa)

VI. CONCLUSIONS

VII. ABBREVIATIONS AND ACRONYMS

- $Bo$  Boiling Number
- $F_{pb}$  Factor for Pool boiling
- $Fr$  Froud Number
- $HTC$  Heat Transfer coefficient (W/m<sup>2</sup>K)
- $h_{fg}$  Latent heat of Vaporization (KJ /Kg)
- $h_{cb}$  Convective boiling HTC (W/m<sup>2</sup>K)
- $m$  Mass Flux
- $Nu$  Nusselt Number
- $Nu_{nb}$  Nusselt Number in Nucleate boiling
- $Re$  Reynolds Number
- $Re_b$  Bubble Reynolds Number
- $P$  Pressure (Bar)
- $q$  Heat Flux (kJ)
- $P_r$  Reduced Pressure
- $w_x$  fourth variable
- $\phi$  Ratio of HTC of flow boiling and convection
- $\mu_l$  Liquid Viscosity (m<sup>2</sup>/s)

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