# A CONDENSATION HEAT TRANSFER CORRELATION FOR INCLINED SMOOTH TUBES

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## ABSTRACT

Correlation models for the prediction of condensation heat transfer performance of inclined smooth tubes are very scarce in literature. Most of the available models are limited to horizontal and vertical tube orientations. This paper presents a correlation model for the prediction of heat transfer coefficient during the convective condensation of R134a in a smooth inclined tube-in-tube condensing heat exchanger subject to diabatic conditions. The authors, in previous investigations presented the experimental data which have been used for the development of the proposed model. In this particular study, the test matrix comprises 260 data test points for inclination angles varying between -90 degrees (downward flow) and + 90 degrees (upward flow), for mass fluxes between 100 kg/m$^2$s and 400 kg/m$^2$s, mean vapour qualities between 0.1 and 0.9 at saturation temperature of 40°C. In the developed model, the effects of the independent variables such as mean vapour quality, mass flux and inclination are well captured. The proposed empirical model is in good agreement with the experimental data and performed better than the other models used for comparison.

## INTRODUCTION

Condensation of refrigerant inside inclined smooth tubes has in recent times received attention due to its application in A- and V-frame heat exchangers. Such heat exchange equipment types have been used especially in remote areas where water is scarce and where air-cooled systems are the best option to sustain cooling of condensers in power plants and refrigeration plants.

There are numerous correlations in literature which may be employed to predict the heat transfer coefficient in horizontal and vertical tube orientations. This is due to the fact that most of the available heat exchange equipment used in the refrigeration and air conditioning systems and other industries are in these orientations. Some of the recent correlation models include those for horizontal tubes [1 – 2], for vertical tubes [3 – 4] and for inclined tubes [5]. For a horizontal tube orientation, Cavallini *et al*. [1] proposed a heat transfer model for smooth tubes of inner diameters greater than 3.0 mm. The model was developed for different types of fluids and thermal conditions. When compared with other correlations, it gives relatively good results. Jung *et al*. [2], in their study on the condensation heat transfer coefficient of pure refrigerants in horizontal smooth tubes with an outer diameter of 9.52 mm and a length of 1.0 m considered the effects of vapour quality and mass flux for various fluids. The investigation was subjected to the following operating conditions: mass fluxes of 100 kg/m$^2$s, 200 kg/m$^2$s and 300 kg/m$^2$s, vapour qualities between 0.1 and 0.9 and heat fluxes of 7.3 to 7.7 kW/m$^2$ at saturation temperature of 40°C. Based on their data they developed a heat transfer coefficient correlation.

On vertical flows, Dalkilic *et al*. [3, 4] experimentally investigated the heat transfer coefficient during the condensation of R134a in downward flow for both laminar and annular flow pattern cases in smooth tubes. They considered mass fluxes ranging between 29 kg/m$^2$s and 515 kg/m$^2$s, saturation temperatures of 40°C to 50°C, heat fluxes between

## NOMENCLATURE

| | | |
|---|---|---|
| *ABS* | [-] | absolute |
| *AD* | [-] | average deviation |
| $c_p$ | [J kg$^{-1}$K$^{-1}$] | specific heat |
| $C_T$ | [-] | constant |
| $d$ | [m] | tube diameter |
| *Eö* | [-] | Eötvös number |
| $g$ | [ms$^{-2}$] | gravitational acceleration |
| $G$ | [kgm$^{-1}$s$^{-2}$] | mass flux |
| $h_{fg}$ | [J kg$^{-1}$] | latent heat |
| *Ja* | [-] | Jakob number, dimensionless |
| $J_G$ | [-] | dimensionless gas velocity |
| $J_G^T$ | [-] | transition dimensionless gas velocity |
| $k$ | [Wm$^{-1}$K$^{-1}$] | thermal conductivity |
| *MAD* | [-] | mean absolute deviation |
| *N* | [-] | number of data points |
| *Pr* | [-] | Prandtl number |
| *Re* | [-] | Reynolds number |
| *T* | [K] | temperature |
| $x$ | [-] | vapour quality |
| $X_{tt}$ | [-] | Martinelli parameter |

Special characters

| | | |
|---|---|---|
| $\alpha$ | [Wm$^{-2}$K$^{-1}$] | heat transfer coefficient |
| $\beta$ | [°] | inclination angle |
| $\mu$ | [kg/m.s] | dynamic viscosity |
| $\rho$ | [kgm$^{-3}$] | density |
| $\sigma$ | [Nm$^{-1}$] | surface tension |

Subscripts

| | |
|---|---|
| *exp* | experiment |
| *l* | liquid |
| *m* | mean |
| *sat* | saturation |
| *tp* | predicted two-phase |
| *v* | vapour |
| *w* | wall |

11.3 kW/m$^2$ and 55.3 kW/m$^2$, and operating pressures between 0.77 MPa and 0.1 MPa for tubes with inner diameters of 7.0 mm and 8.1 mm and a length of 0.5 m. The effects of mean vapour quality, mass flux and saturation temperature were studied on the heat transfer. Results showed that the heat transfer coefficient was a function of these parameters and that an increase in the mean vapour quality and mass flux increased the heat transfer coefficient, where-as the converse was the case for the saturation temperature. A new model was proposed and was compared with earlier models.

Akhavan-Behabadi *et al*. [5] experimentally investigated the condensation of R 134a in an inclined microfinned tube which had an inner diameter of 8.92 mm. The experimental conditions that were considered are mass fluxes of 54 kg/m$^2$s, 81 kg/m$^2$s and 107 kg/m$^2$s; mean vapour qualities between 0.2 and 0.8; inclination angles between -90° and +90° for a saturation temperature of 32°C. Based on their experimental data, an optimum inclination angle of +30° (upward flow) was obtained and a heat transfer correlation was developed.

Lips and Meyer [6], in their experimental investigation of heat transfer in an inclined smooth tube during the convective condensation of R134a considered different conditions ranging from mass fluxes between 200 kg/m$^2$s and 600 kg/m$^2$s, mean vapour qualities between 0.1 and 0.9, inclination angles between -90° and +90° at saturation temperature of 40°C. Conclusively, they studied the implications of the various parameters on the heat transfer coefficient. In a follow-on study Meyer *et al*. [7] investigated the effects of saturation temperature and inclination angle on convective heat transfer during condensation of R134a in an inclined smooth copper tube with an inner diameter of 8.38 mm. Similarly, inclination angles were ranged from -90° to +90° and vapour qualities between 0.1 and 0.9 were investigated. However, lower mass fluxes between 100 kg/m$^2$s and 400 kg/m$^2$s were tested and a wider saturation temperatures range between 30°C and 50°C was used. The results showed that the saturation temperature and inclination angle both strongly influenced the heat transfer coefficient. With respect to saturation temperature, an increase in saturation temperature generally led to a decrease in heat transfer coefficient irrespective of the inclination angle, similar to the findings by Dalkilic *et al.* [3, 4].

In this current study, a simple heat transfer coefficient correlation is developed based on our experimental data sets [7]. The present model was compared with our experimental data and some of the recent models available in the literature.

## TEST MATRIX

The experimental setup consisted of a pre-condenser, test-condenser section and a post-condenser. The test section was made up of a tube-in-tube heat exchanger in which R134a was transported through the inner tube and water through the annulus in a counter current arrangement. The test section had an inner tube of inner and outer diameters of 8.38 mm ($d$) and 9.55 mm respectively while the outer tube had an inner diameter of 15.9 mm. The test condenser could be inclined between -90$^o$ (vertical downward flow) and +90$^o$ (vertical upward flow) and was connected to the rest of the test facility via a high pressure flexible hose. Since the test condenser was water-cooled, the heat flux along the length of the tube was proportional to the difference between the saturation temperature in the R134a (constant at 40°C) and the local water temperature in the annulus. Water entered at approximately 15°C and exited at approximately 39.5°C. The local heat flux was therefore not uniform, neither was the wall temperature constant along the heat exchanger length. Details of the experimental setup and data procedure can be seen in the works of Meyer and his co-researchers [6 - 10]. For the purpose of this paper, 260 of the test data points for a saturation temperature of 40°C are used in this study. The data-base comprises 20 data sets as listed in Table 1 in terms of the mass flux, $G$, and mean vapour quality, $x_m$. Each for thirteen tube inclination angles considered ($\beta$ = -90°, -60° - 30° - 15° - 10°, -5°, 0°, 5°, 10° ,15°, 30°, 60°, 90°). The calculated experimental uncertainties for the heat transfer coefficient ranged between 0.81% and 7.9%.

## PROPOSED HEAT TRANSFER MODEL

As mentioned earlier, few heat transfer coefficient models have been developed to predict inclined tube flow. The proposed empirical model that we present here depends on the flow categorization observed during the experiment. The flows were categorized into two classifications in consonance with the works of Cavallini *et al.* [1]. The first classification comprises the annular, annular-wavy, intermittent and misty flow types. These flows are gravity and temperature difference independent. The second classification comprises smooth stratified and stratified-wavy flow types. These fall within the gravity and temperature difference dependent regime. These two flow classifications are to be treated differently.

Following the model by Cavallini *et al*., the dimensionless gas velocity, $J_G$ is used to describe the classification in which the flow lies. This velocity is defined as follows in terms of the mass flux, vapour quality, tube diameter, gravitation acceleration, $g$, and the liquid and gas phase densities, $\rho_l$ and $\rho_v$:

**Table 1** Current database used in this paper for $T_{sat}$ = 40°C.

| Data-set | $G$ [kg/m$^2$s] | $x_m$ [-] |
|---|---|---|
| 1 | 100 | 0.25 |
| 2 | | 0.5 |
| 3 | | 0.62 |
| 4 | | 0.75 |
| 5 | 200 | 0.1 |
| 6 | | 0.25 |
| 7 | | 0.5 |
| 8 | | 0.62 |
| 9 | | 0.75 |
| 10 | | 0.9 |
| 11 | 300 | 0.1 |
| 12 | | 0.25 |
| 13 | | 0.5 |
| 14 | | 0.62 |
| 15 | | 0.75 |
| 16 | | 0.9 |
| 17 | 400 | 0.5 |
| 18 | | 0.62 |
| 19 | | 0.75 |
| 20 | | 0.9 |

$$J_G = \frac{xG}{[gd\rho_v(\rho_l - \rho_v)]^{0.5}} \quad (1)$$

The transition value, $J_G^T$, which depends on the type of fluid and inclination angle, is given in equation (2) as a function of the Martinelli parameter, $X_{tt}$, which is used to account for the turbulent nature of the flow assuming the liquid and vapour are both turbulent.

$$J_G^T = \{[7.5/(4.3X_{tt}^{1.111} + 1)]^{-3} + C_T^{-3}\}^{-\frac{1}{3}} \quad (2)$$

where, $X_{tt}$ is the Martinelli parameter given as:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \quad (3)$$

$J_G$ values greater than or equal to $J_G^T$ indicate flow types that are temperature difference and gravity independent, while the opposite is true for $J_G < J_G^T$. Compared to the model by Cavallini *et al.* [1], $C_T$ is modified and equated to 2.4 to accommodate the effect of inclination especially around the transition line. This value was obtained by fitting the experimental data to the transition criteria. Higher and lower value give incorrect predictions of the transition criteria used to categorise the flow into temperature difference independent and dependent flow especially during the inclination. Higher values overestimate the gravity dependent regime (i.e. underestimate the gravity independent regime). The converse is the case when it is lower. This is needed since the Cavallini *et al.* [1] model was developed for horizontal flow and could not correctly predict the transition for inclined flows. The modified transitional dimensionless gas velocity is plotted in Figure 1 in terms of the Martinelli parameter. A typical data set for mass flux of 300 kg/m$^2$s and vapour quality of 0.5 is shown in Figure 1b. Using the Cavallini *et al.* [1], all the data is categorised in the temperature or gravity dependent regime whereas the flow pattern showed that intermittent flow occurred between -5$^o$ and +60$^o$, stratified wavy between -10$^o$ and -60$^o$ and annular at -90$^o$ and +90$^o$. This shows that the proposed model is able to correctly capture the flow distribution in inclined tubes at the transition regime.

For the temperature difference or gravity independent flows ($J_G \geq J_G^T$), equation (3) is used to predict the two phase heat transfer coefficient, $\alpha_{tp}$ in terms of, $X_{tt}$ $J_G, J_G^T$, and the Jakob's number, $Ja$:

$$\alpha_{tp} = \alpha_l(1 + 0.8247X_{tt}^{-0.2245}Ja^{-0.23063}\left(\frac{J_G}{J_G^T}\right)^{-0.20727}) \quad (4)$$

Here $\alpha_l$ is the hypothetical heat transfer coefficient if only a liquid phase was present in the tube and is modelled with the Dittus-Boelter equation given in equation (5) based on the liquid phase Reynolds number, $Re_l$ and Prandtl number, $Pr_l$:

$$\alpha_l = 0.023Re_l^{0.8}Pr_l^{0.4}\,{}^{k_l}/_{d} \quad (5)$$

$$Re_l = G(1-x)d/\mu_l \quad (6)$$

The Jacob's number represents the ratio of sensible to latent heat and takes care of the effect of superheating and subcooling and also accounts for the effects of heat capacity of the liquid, $c_{p,l}$, the difference in the saturation and wall temperatures ($T_{sat}$ and $T_w$) and the latent heat of vapourization, $h_{fg}$:

$$Ja = \frac{c_{p,l}(T_{sat} - T_w)}{h_{fg}} \quad (7)$$

For the temperature difference or gravity dependent flows ($J_G < J_G^T$), equations (8) and (9) are functions of the inclination angle, $\beta$ and are used to determine the two phase heat transfer coefficient. Equation (8) predicts the heat transfer coefficient for inclination angles between -90$^o$ and -30$^o$ while equation (9) calculates the heat transfer coefficient for inclination angles between -30$^o$ and +90$^o$.

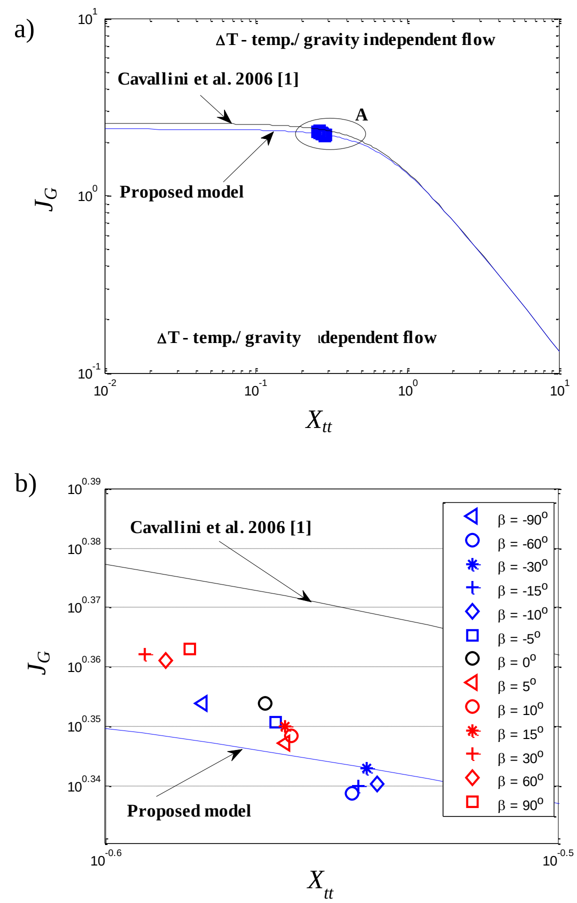


**Figure 1** a) Transition curves between the gravity or temperature difference independent and dependent flow regimes and b) Prediction of a typical data set for mass flux of 300 kg/m$^2$s, vapour quality of 0.5 at the transition regime using Cavallini *et al.* [1] and the proposed model.

$$\alpha_{tp} = \alpha_l \left(1 + 0.0422 X_{tt}^{-0.2056} Ja^{-0.5672} \left(\frac{J_G}{J_G^t}\right)^{-0.505} E\ddot{o}^{0.0316} (3 + \cos(\beta))^{1.3492}\right)$$

For -90° ≤ $\beta$ < -30° (8)

$$\alpha_{tp} = \alpha_l \left(1 + 0.5191 X_{tt}^{-0.3153} Ja^{-0.3214} \left(\frac{J_G}{J_G^t}\right)^{-0.6393} (\cos(\beta) + \sin(\beta))^{-0.1506}\right)$$

For -30° ≤ $\beta$ < +90° (9)

Here the Eötvös number, *Eö*, takes care of the hydrodynamic interaction of buoyancy and surface tension. It accounts for the effects of geometry, gravity, density and surface tension in the flow.

$$E\ddot{o} = \frac{(\rho_l - \rho_v) g d^2}{\sigma} \qquad (10)$$

## MODEL COMPARISON WITH EXPERIMENTAL RESULTS

Figures 2a and 2b depict the predicted heat transfer coefficients (equations 4, 8 or 9) versus experimental results according to classification of gravity or temperature difference independent and dependent flow regimes respectively. For the gravity independent regime, all the experimental data is predicted within a ±10% error band while for the gravity dependent regime, most of the data (98.6%) are within the ±15% error margins.

The average deviation (defined in equation 11) and mean absolute deviation (defined in equation 12) are employed to check the deviation of the predicted values from the experimental data. The average and mean absolute deviations are 0.34% and 4.35% respectively. These values show that the model is relatively good in its ability to predict the experimental data.

$$AD = \frac{1}{N} \sum_{1}^{N} \left[ \frac{(\alpha_{tp} - \alpha_{exp}) * 100\%}{\alpha_{exp}} \right] \qquad (11)$$

$$MAD = \frac{1}{N} \sum_{1}^{N} ABS \left[ \frac{(\alpha_{tp} - \alpha_{exp}) * 100\%}{\alpha_{exp}} \right] \qquad (12)$$

## OTHER MODELS IN COMPARISON WITH EXPERIMENTAL RESULTS

The current datasets were also used to check the accuracy of the prediction of the Cavallini *et al.* [1] and Shah [11, 12] models. The correlations of Shah were developed for horizontal, vertical downward and slightly downward orientations. Figure 3 presents data points for all inclination angles including horizontal, vertical and inclined for these correlations. The results indicate that significantly more of data points are predicted within the ±15% error margins when using the Cavallini *et al.* [1] correlation than when using the the Shah correlations[11, 12]. The Cavallini *et al.* [1] correlation which was developed for a horizontal tube orientation therefore has a better prediction performance. This could be because the model was based on the core principle that two-phase flow can largely be categorised into the gravity and/or temperature difference dependent and independent regimes, which are influenced by the dominance of gravitational and shear forces respectively. The relative performance of the correlations in terms of the average and mean average deviation is given in Table 2.

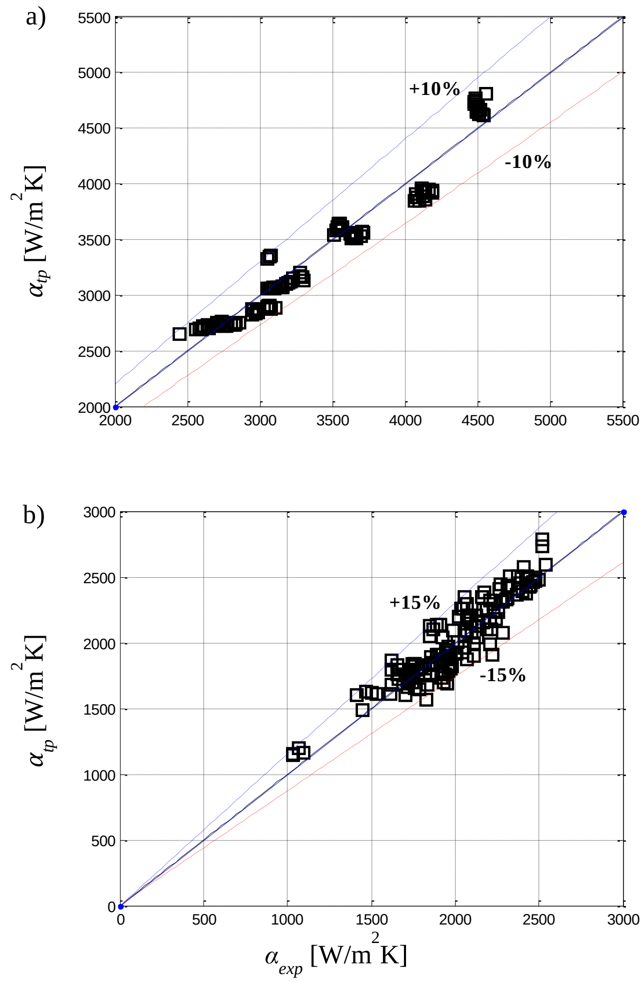


**Figure 2** Comparison of the developed model correlation with experimental data for gravity and/or temperature difference a) independent and b) dependent regimes.

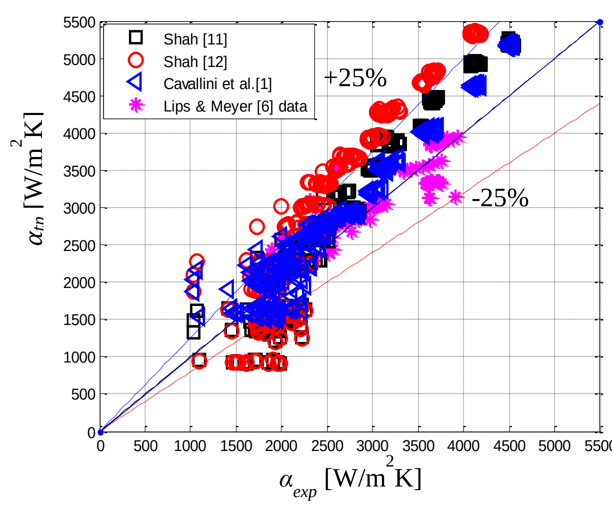


**Figure 3** Comparison of the performance of the models of Cavallini *et al.* [1] and Shah [11, 12] with experimental data.

**Table 2** Comparisons of the average and mean average deviations as obtained with different correlations.

| | Dataset | Average deviation | Mean average deviation |
|---|---|---|---|
| Equations (4), (8) and (9) | Current | 0.34% | 4.35% |
| | Lips and Meyer [6] | 8.94% | 4.81% |
| Cavallini *et al*. [1] | Current | 9.07% | 13.24% |
| Shah [11] | Current | 2.53% | 19.41% |
| Shah [12] | Current | 16.77% | 28.38% |

Also included is the performance of equations (4), (8) and (9) for the data of Lips and Meyer [6]. The Lips and Meyer data in Figure 4 was analysed with the current proposed model and are included for comparison purposes. From Table 2 it can be seen that the current proposed correlation outperformed the other three correlations significantly.

## EVALUATION OF PROPOSED MODEL

Figure 4 presents the ratio of the predicted to the experimental heat transfer coefficient as a function of mass flux for the 260 data points in the current data set. The results show that all the data for mass fluxes of 300 and 400 kg/m$^2$s fall within ± 15% from the experimental results while one data point each for 100 kg/m$^2$s and 200 kg/m$^2$s fall outside. Therefore, of the 260 data points, 258 points (99.2%) are within the ± 15% deviation band. Figure 5 presents the ratio of the predicted to experimental heat transfer coefficient as a function of the inclination angle. Results reveal that all the data except a minimal number of points for inclination angles of $\beta$ = +15$^o$ and +90$^o$ are within the ± 15% deviation. $\beta$ = +15$^o$ and +90$^o$ account for 50% each of the data outside the ±15% deviation. Figure 6 indicates the result of the ratio of the predicted model to experimental heat transfer coefficient as a function of the mean vapour quality. The results show that most of the data points fall within a ±15% deviation. All of the data for mean vapour qualities of 0.1, 0.5, 0.62 and 0.9 fall within the deviation while one data each for qualities of 0.25 and 0.75 are outside this range..

Next we apply the current model to predict the experimental data to see how it behaves with respect to inclination for both temperature dependent and independent regimes. Figures 7 and 8 show the comparison of the model prediction with experimental data. Figure 7 depicts the variation of inclination angle with heat transfer coefficient for both proposed model and experimental data for mean vapour qualities of 0.1, 0.25, 0.5, 0.62, 0.75 and 0.9 for $T_{sat}$ = 40 $^o$C and $G$ = 300 kg/m$^2$s. The figure reveals that the model has the capability to predict the trend behaviour for both regimes types relatively well. The impact of the inclination angle is well captured for all vapour qualities except for $x_m$ = 0.75 when $\beta$ is between -90° and -30°.For all the inclination angles, the largest error of -14.34% was obtained when $x_m$ = 0.1 and $\beta$ = -90$^o$ while the lowest error of -0.19% was obtained for $x_m$ = 0.25 and $\beta$ = 0$^o$. In Figure 8, the result of the proposed model and experimental data are compared for mass flux of 100 kg/m$^2$s, 200 kg/m$^2$s, 300 kg/m$^2$s and 400 kg/m$^2$s for $T_{sat}$ = 40$^o$C and $x_m$ = 0.5. The result shows a very good agreement between the model predictions and the experimental results.

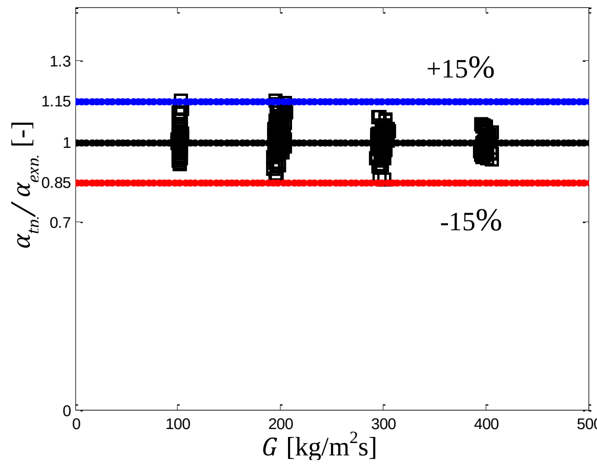


**Figure 4** Variation of the ratio of predicted to experimental heat transfer coefficient as a function of mass flux.

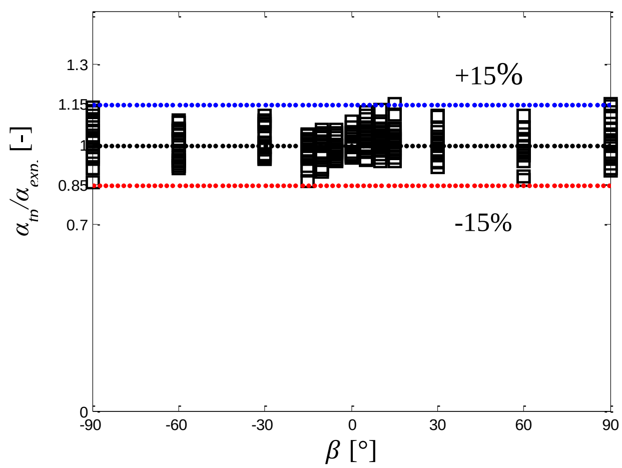


**Figure 5** Variation of the ratio of predicted to experimental heat transfer coefficient as a function of inclination angle.

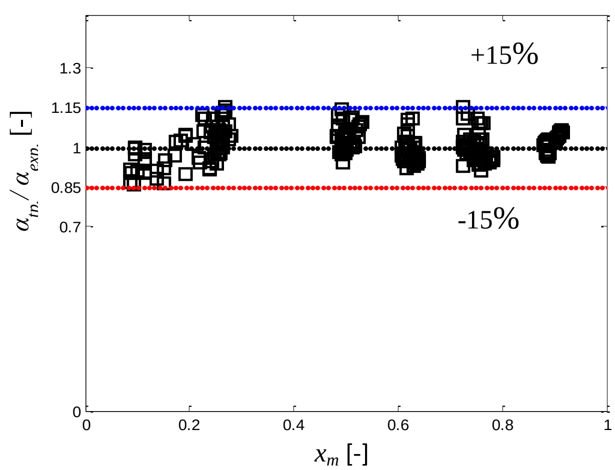


**Figure 6** Variation of the ratio of predicted to experimental heat transfer coefficient as a function of mean vapour quality.

While for $G$ = 100 kg/m$^2$s and 300 kg/m$^2$s, better predictions were obtained during the upward flow, the converse was the case for $G$ = 200 kg/m$^2$s and 400 kg/m$^2$s. In all, data for $G$ = 200 kg/m$^2$s are worse predicted though mostly within the ± 15% error. The maximum error of +15.22 % was obtained for $G$ = 200 kg/m$^2$s, $x_m$ = 0.25 and $\beta$ = +15$^o$ while the minimum was -0.03% for $G$ = 100 kg/m$^2$s, $x_m$ = 0.5 and $\beta$ = +15$^o$.

## CONCLUSIONS

A new heat transfer coefficient correlation model is developed for an inclined tube for experimental conditions 100 kg/m$^2$s ≤ $G$ ≤ 400 kg/m$^2$s, 0.1 ≤ $x_m$ ≤ 0.9, -90$^o$ ≤ $\beta$ ≤ +90$^o$ and $T_{sat}$ = 40 $^o$C in smooth tube of internal diameter of 8.38 mm subject to diabatic condition. The predictions of the proposed empirical correlation model shows a good agreement with the experimental data collected for inclined tube with an overall average and mean absolute deviations of 0.34% and 4.35% accuracy respectively.

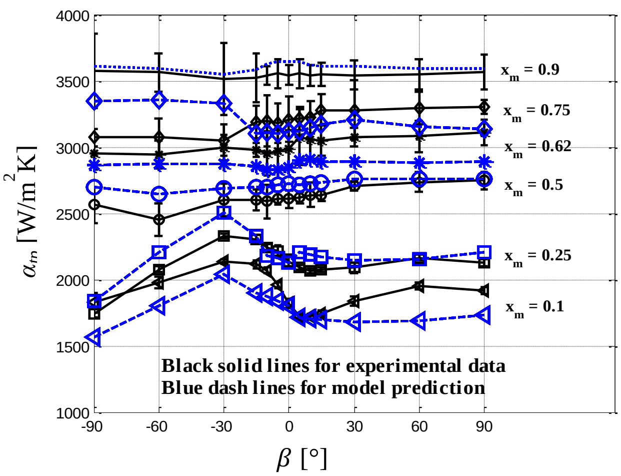


**Figure 7** Comparison of present correlation model with experimental data points as a function of inclination angle for different mean vapour quality for $T_{sat}$ = 40 $^o$C and $G$ = 300 kg/m$^2$s.

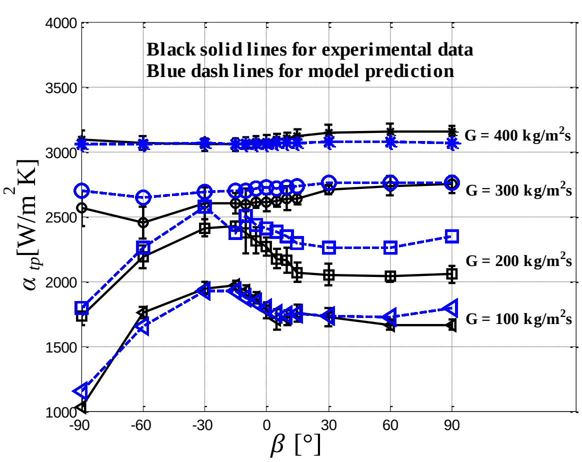


**Figure 8** Comparison of proposed correlation model with experimental data points as a function of inclination angle for different mass fluxes for $T_{sat}$ = 40 $^o$C and $x_m$ = 0.5.


## AKNOWLEDGEMENT

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