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# Empirical Correlation of Refrigerant HC290/HC600a/ HFC407C Mixture in Adiabatic Capillary Tube Using Statistical Experimental Design

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## ABSTRACT

HCFCs, in addition to destroying the ozone layer, have been recognized as a contributing factor that increases global warming. It is widely used as working fluid in window air-conditioning system, where capillary tube serves as an expansion device. Literature reports have shown that no single refrigerant can solve the problem of ozone layer depletion and global warming. Refrigerant HC290/HC600a/HFC407C mixture, an eco-friendly refrigerant, has been recognized as an alternative to HCFC22. The objective of this study is to, for cost effectiveness, develop an empirical correlation to predict the refrigerant HC290/ HC600a/HFC407C mixture mass flow rate using statistical experimental design approach. A review of relevant literature shows that refrigerant's mass flow rate depends on condensing temperature, degree of subcooling, inner diameter and length of capillary tube. The relationship between the mass flow rate and the four independent variables was established as an empirical mathematical correlation using central composite design (CCD), a response surface methodology (RSM). This empirical correlation was examined using analysis of variance (ANOVA) of 5% level of significance. The results of these analysis showed that the correlation fitted well with the experimental data yielding an average and standard deviation of 1.05% and 2.62%, respectively. The validity of the present correlation was further assessed by comparing it with published empirical correlation in literature and the result showed that the present correlation is consistent.

*Keywords*: Ozone layer, air-conditioning, capillary tube, refrigerant, empirical correlation

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## INTRODUCTION

To some extent, most people are aware of the consequences of ozone layer depletion and global warming, and thus, changes that address these issues are of utmost importance. Efforts to eliminate non-eco-friendly refrigerants such as chlorofluorocarbon (CFCs) and hydro chlorofluorocarbons (HCFCs) in refrigeration and air-conditioning industries are ongoing. In modern refrigeration and air-conditioning systems, capillary tube, a drawn copper tube with diameter ranging from 0.5 to 2 mm and length from 1.5 to 6 m, is often used as an expansion and metering device. This is due to its simplicity in construction, low cost, no moving part and requires small starting torque of the compressor. Capillary tube has a simple geometric configuration but refrigerant flow in it is complex. The performance of a refrigeration system depends on appropriate selection of length and inner diameter of the capillary tube for a given input conditions so that the desired mass flow rate can be achieved. Design of refrigeration system using a new refrigerant requires a fresh study of this alternative refrigerant flow in the capillary tube because of the differences in the thermophysical properties of the conventional and the new refrigerants.

The refrigerant behaviour through capillary tube has been studied extensively in both numerical and experimental approach. In the numerical approach, three different types of models are commonly used – two-phase homogenous, separated flow and drift flux models. In a homogenous model, the two-phase liquid/vapour mixture is simulated using mean refrigerant properties (Bansal & Rupasinghe, 1998; Kritsadathikarn *et al.*, 2002; Kumar *et al.*, 2009; Sami & Tribes, 1998; Shodiya *et al.*, 2011b; Wongwises & Chingulpitak, 2010; Wongwises & Pirompak, 2001; Wongwises & Suchatawut, 2003; Zhou & Zhang, 2006; Kim *et al.*, 2011; Shodiya *et al.*, 2012). Likewise, in the separated flow model, the slip that exists between the liquid and vapour is considered and a mixture variable called void fraction is introduced to the conservation equations (Wongwises *et al.*, 2000). In the drift flux model, the entire two-phase liquid-vapor mixture is considered when formulating the conservation equations (Liang & Wong, 2001).

Practically speaking, these numerical simulations that were used for analyzing and designing capillary tubes requires some computer programming skills by the users, as a result, it has not been widely used by the capillary tube engineering designers. In order to simplify these models, many researchers (Yilmaz & Unal, 1996; Ding *et al.*, 1999; Zhang & Ding, 2001; Hermes *et al.*, 2010) developed an approximate analytic model for the analysis and designing of the tube. Though, an appreciable success was recorded, but, their models resulted in an iterative calculation, as such, the analytic model is still not an explicit solution.

Unlike the numerical simulation and approximate analytic models, empirical correlations are simple to operate and more convenient for the capillary tube engineering designers. As such, several investigators carried out studies in order to develop empirical correlation that can be used to predict refrigerant mass flow rate in capillary tubes (Choi *et al.*, 2004; Choi *et al.*, 2003; Fiorelli *et al.*, 2002; Jabaraj *et al.*, 2006; Kim *et al.*, 2002; Park *et al.*, 2007; Shodiya *et al.*, 2011a; Vinš & Vacek, 2009; Zhou & Zhang, 2006). In developing these correlations, experimental data of various refrigerants (eco-friendly and non-eco-friendly) and a dimensionless parameter based on Buckingham pi theorem were used.

All the aforementioned empirical correlations do not use statistical experimental design to investigate the behaviour of refrigerant flow in capillary tube and develop their correlations. Statistical experimental design is economical because it requires a relatively small number of experiments and yet able to be analyzed by using statistical methods to yield results in valued and objective conclusions. This particular approach of experimental design is very important if meaningful conclusions are to be drawn from the data. A statistically designed approach is a systematic and scientific approach for planning and analyzing data when a problem that involves experimental errors is considered (Montgomery, 2005). Central composite design (CCD), which is a Response surface method (RSM), is one of the statistical designs of the experimental methods. It is a combination of the statistical and mathematical techniques used for planning and analyzing problems in which the output variables (responses) are influenced by input factors and the goal is to optimize the response(s). Using RSM, the interactions between the input factors and the response(s) can be established (Montgomery, 2005).

Research applying statistical experimental design to develop an empirical correlation to predict the refrigerant mass flow rate in capillary tubes is rather limited (see Bittle & Pate, 1996; Bittle *et al.*, 1995; Melo *et al.*, 2002). For example, Melo *et al*. (2002) performed an experiment using statistical factorial design of experiment on concentric diabatic capillary tube with R600a as working fluid. They proposed empirical correlations of refrigerant mass flow rate based on their experimental results. The empirical correlation is in good agreement with their experimental data.

However, the refrigerants used in those studies are mostly synthetic and contain chlorine and fluorine that cause depletion of ozone layer and lead to global warming. The major objective of this paper is to develop a new empirical correlation with new refrigerant mixture containing 20% HC (HC600a and HC290) and HFC407C to predict refrigerant mass flow rate through adiabatic capillary tube using statistical design of experiment. It should be noted that the main advantage of this design of experiment is to obtain maximum information with a minimum amount of experiment performed.

## CORRELATION DEVELOPMENT

### *Data Source*

As observed in some previous studies (see Li *et al.*, 1990; Lin *et al.*, 1991; Melo *et al.*, 1992), the refrigerant mass flow rate (m) in capillary tube depends on the length of capillary tube (L), inner diameter (D), condensing temperature ($T_{cond}$) and degree of subcooling ($T_{sub}$). Though the refrigerant properties (thermodynamic and transport) are also important in predicting the refrigerant mass flow rate, the effects of these properties have been to some extent taken care of by condensing temperature and degree of subcooling. As a result, these four factors are considered as independent variables and mass flow rate as a dependent variable. Design expert (version 7.1, Stat-Ease, Inc., Minneapolis, USA), an experimental design software, was used for this study. In order to reduce the experiment to be performed, which is the main advantage of this approach, statistical technique, central composite design (CCD), the most popular RSM design, was used to construct the test matrix. A four factor CCD rotatable option (four factors: 4! =24), with six replicate at the centre point, was employed in designing the experimental test. A CCD rotatable option is applicable to design factors less than six. The centre points are usually repeated 4-6 times to get a good estimate of experimental error. In this study, six centre points were used to achieve an optimal performance. The total experimental data points that are now required to complete the experiment are 30 (24 from factors and 6 from centre points). In order to determine the numerical values of each design variable to be used to perform the experiment, a two-level alpha (low and high levels) was used. The lowest and highest values of each design parameter were input into the design expert software. Thereafter, the software generated the experiment to be performed. The ranges and level of factors used are shown in Table 1.

TABLE 1
Experimental range and level of central composite design

| Variables | Range and levels | | | | |
|---|---|---|---|---|---|
| | -2 | -1 | 0 | +1 | +2 |
| Condenser temperature, $T_{cond.}$ (°C) | 37 | 42 | 44.5 | 47 | 52 |
| Degree of subcooling, $T_{sub}$.(°C) | 2 | 5 | 8 | 11 | 14 |
| Length of capillary tube, L (m) | 0.75 | 1.00 | 1.25 | 1.5 | 1.75 |
| Diameter of capillary tube, D (mm) | 1.12 | 1.19 | 1.27 | 1.33 | 1.40 |

## RESULTS AND DISCUSSION

The design expert software (version 7.1, Stat-Ease, Inc., Minneapolis, USA) was used for the regression and graphical analysis of the data. Considering the values of each design parameter generated from the software, the responses were carefully selected from the experimental data of Jabaraj *et al*. (2006). The total experimental data points of Jabaraj *et al*. (2006) were 200. In selecting the experimental data points, some of these points were not directly available in the experimental data of Jabaraj *et al.* (2006). As a result, the empirical model developed by Jabaraj *et al.* (2006) from their experimental data was used to determine these points. The method of using the existing model to generate data to be used for developing new correlations has been used by many researchers (Bansal & Rupasinghe, 1996; Wongwises & Trisaksri, 2003; Shodiya *et al.*, 2011a; Sarker & Jeong, 2012).

The measured mass flow rates and their associated input parameters according to the experimental design are given in Table 2. The application of RSM with the design expert software yielded the following regression equation, which is an empirical relationship between the mass flow rate and the input variables given in Eq. 1. In developing this equation, the software used least square formulation to minimize the errors between the mass flow rate calculated by the regression equation and the measured data.

$$\begin{aligned} m = & -93.7361 + 2.4854T_{cond} + 0.8050T_{sub} - 10.4512L + 64.3006D \\ & - 0.005241T_{cond}T_{sub} + 0.03114T_{cond}L - 0.1925T_{cond}D \\ & + 0.03217T_{sub}L + 0.1329T_{sub}D + 2.9701LD - 0.02314T_{cond}^2 \\ & - 0.006352T_{sub}^2 + 0.1430L^2 - 16.2679D^2 \end{aligned} \quad (1)$$

TABLE 2
CCD response result for four input factors

| Run | Condensing Temperature (°C) – Factor 1 | Degree of Subcooling (°C) – Factor 2 | Capillary tube Length (m) – Factor 3 | Capillary tube Diameter (mm) – Factor 4 | Mass flow rate (g/s) -Response |
|---|---|---|---|---|---|
| 1 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |
| 2 | 44.5 | 8 | 1.25 | 1.40 | 14.84 |
| 3 | 47.0 | 11 | 1.75 | 1.33 | 12.05 |
| 4 | 42.0 | 11 | 1.75 | 1.33 | 11.32 |
| 5 | 42.0 | 11 | 1.75 | 1.19 | 8.89 |
| 6 | 44.5 | 8 | 1.25 | 1.12 | 9.68 |
| 7 | 44.5 | 8 | 1.75 | 1.27 | 10.72 |
| 8 | 47.0 | 5 | 1.50 | 1.12 | 7.29 |
| 9 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |
| 10 | 47.0 | 11 | 1.00 | 1.27 | 14.36 |
| 11 | 42.0 | 5 | 1.00 | 1.12 | 8.76 |
| 12 | 42.0 | 11 | 1.00 | 1.27 | 13.61 |
| 13 | 47.0 | 5 | 1.50 | 1.12 | 7.29 |
| 14 | 44.5 | 14 | 1.25 | 1.27 | 14.44 |
| 15 | 44.5 | 2 | 1.25 | 1.27 | 10.39 |
| 16 | 47.0 | 5 | 0.75 | 1.33 | 14.62 |
| 17 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |
| 18 | 42.0 | 5 | 1.75 | 1.19 | 6.47 |
| 19 | 42.0 | 5 | 1.75 | 1.33 | 8.90 |
| 20 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |
| 21 | 44.5 | 8 | 0.75 | 1.27 | 15.12 |
| 22 | 47.0 | 11 | 0.75 | 1.19 | 14.69 |
| 23 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |
| 24 | 42.0 | 11 | 1.25 | 1.19 | 10.81 |
| 25 | 37.0 | 8 | 1.25 | 1.27 | 9.96 |
| 26 | 42.0 | 5 | 1.00 | 1.40 | 13.54 |
| 27 | 47.0 | 5 | 1.00 | 1.40 | 14.58 |
| 28 | 47.0 | 11 | 1.50 | 1.12 | 9.57 |
| 29 | 52.0 | 8 | 1.25 | 1.27 | 12.38 |
| 30 | 44.5 | 8 | 1.25 | 1.27 | 12.26 |

The fitting of the model can be checked using several criteria. The Analysis of Variance (ANOVA) for the empirical correlation model is summarized in Table 3. A model is significant at 95% confidence level if Fisher F-test has a probability value (Prob > F) less than 0.05. The F-test for lack of fit (LOF) describes the deviation of the actual points from the fitted surface, relative to pure error (Anderson & Whitcomb, 2005). Preferable is a large value of Prob > F for LOF which is greater than 0.05. For coefficient of determination ($R^2$), a higher value is preferred and a reasonable agreement with adjusted $R^2$ is crucial (Ghafari *et al.*, 2009). Adequate precision (AP) can be defined as a measure of experimental signal to noise ratio (Anderson & Whitcomb, 2005). AP that exceeds 4 usually indicates that the model will give reasonable performance in prediction. PRESS is the prediction error sum of squares which is a measure of how well the model for the experiment is likely to predict the response in the new experiment. The standard deviation (SD), coefficient of variance (CV), and PRESS values are preferred to be small (Montgomery, 2005).

As shown in Table 3, the empirical correlation regression model (Eq.1) is a significant model since its Prob>F value is less than 0.05. In addition, AP, SD and PRESS for the regression model are satisfactory since the value of AP is more than 4. Similarly, SD, CV and also PRESS values are also small (see Table 3).

TABLE 3
ANOVA results for mass flow rate response parameter

| Response | Model F Value | Prob >F | LOF Prob >F | $R^2$ | Adjusted $R^2$ | AP | SD | CV | PRESS |
|---|---|---|---|---|---|---|---|---|---|
| Mass flow rate | 202.99 | 0.0001 | 0.038 | 0.9705 | 0.9654 | 69.92 | 0.0448 | 1.05 | 0.0528 |

Fig.1 compares the mass flow rate experimental data of refrigerant with the predicted data obtained from equation 1. The value of $R^2$ for the predicted mass flow rate model is 0.9705, showing that the model is adequate enough to explain most of the variability of the experimental data. The absolute deviation or the difference between the calculated mass flow rate and the measured one is about 0.24g/s.

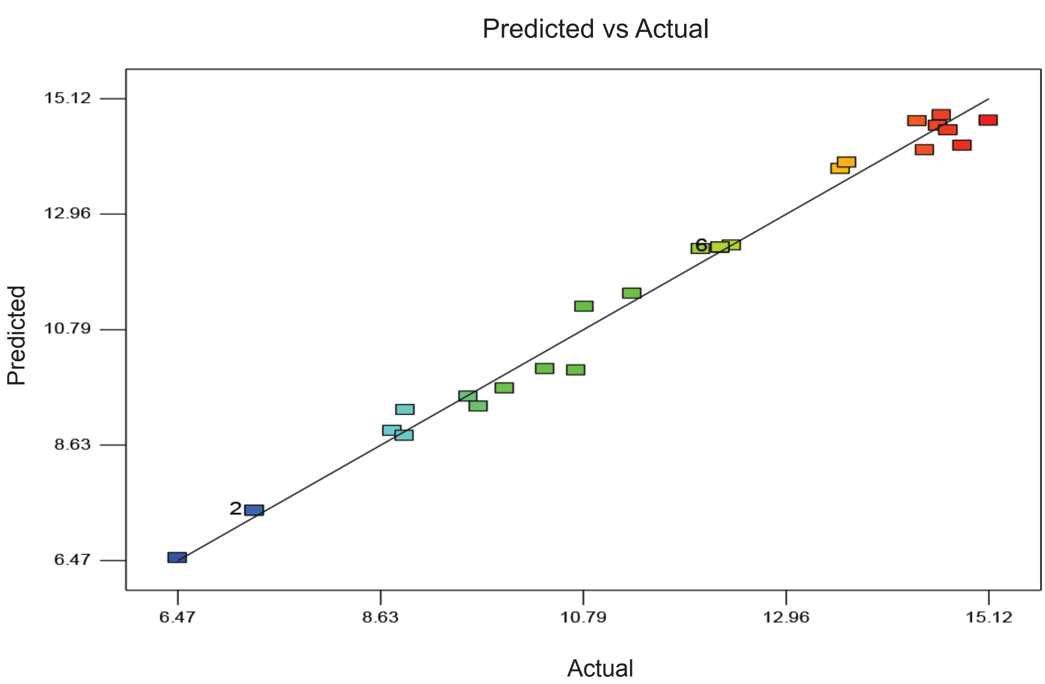


Fig.1. Predicted vs. actual values plot for refrigerant mass flow rate

To further validate Eq. (1), its mass flow rate predictions and the predictions from Jabaraj *et al*.'s (2006) empirical correlation was compared with the measured data as shown in Fig.2. The figure reveals that these two correlation predictions of mass flow rates are in good agreement with the measured data within a deviation of ±5%. About 93% of these predicted mass flow rates fall within this range. This assessment shows that the present correlation is consistent with the correlation of Jabaraj *et al*. (2006).

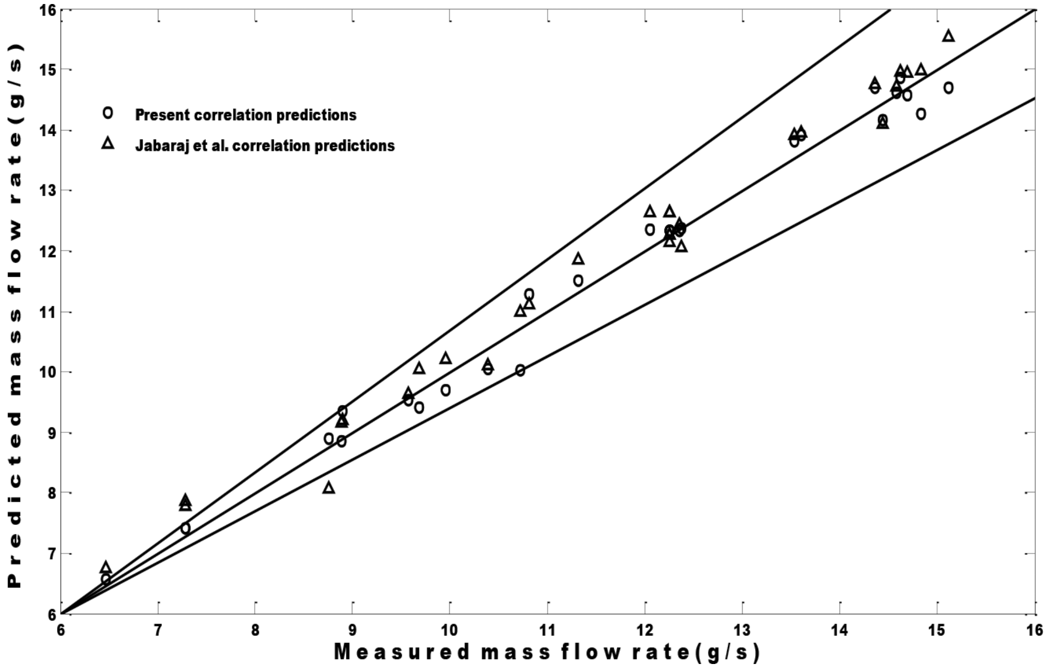


Fig.2. A comparison of the mass flow rate predictions with the measured data

The fitted model from equation (1) can be used to empirically determine the response function over the experimental region. The contour plot helps in assessing the effect of any two variables in combination on the response quality. A 3-D graphical surface plot illustrates the response value of the dependent variables.

It is a well-known fact in literature that the refrigerants mass flow rates increase with the increases in condensing temperature and degree of subcooling. The mass flow rate is strongly dependent on the length and inner diameter of the capillary tube. Fig.3 shows the effects of condensing temperature and degree of subcooling on mass flow rate. The optimum point is obtained on the coordinates of the curve lines (Fig.3). Fig.4 also shows the 3-D graphical surface plot of mass flow rate with the degree of subcooling and condensing temperature. In this figure, there is an increase in mass flow rate as the degree of subcooling increases. This is due to the fact that increased subcooling leads to increased liquid phase, and as a result, an increase in the mass flow rate. The liquid phase offers lesser resistance to the refrigerant flow compared to the vapour/ liquid phase in the capillary tube.

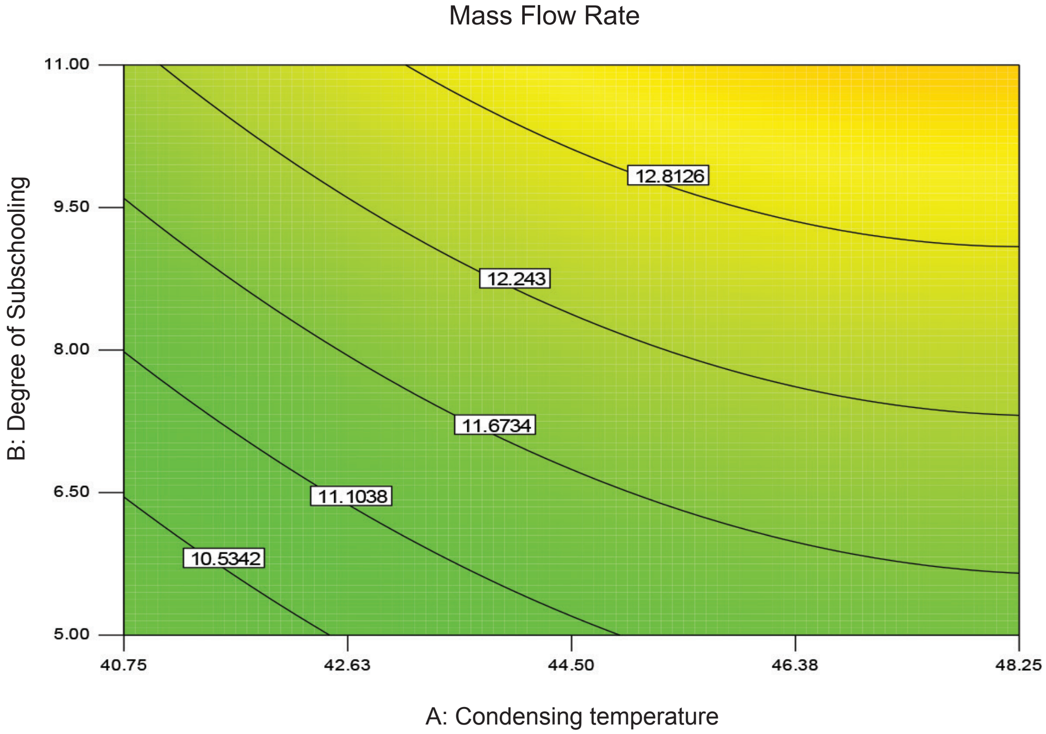


Fig.3: A contour surface plot of mass flow rate as a function of degree of subcooling and condensing temperature

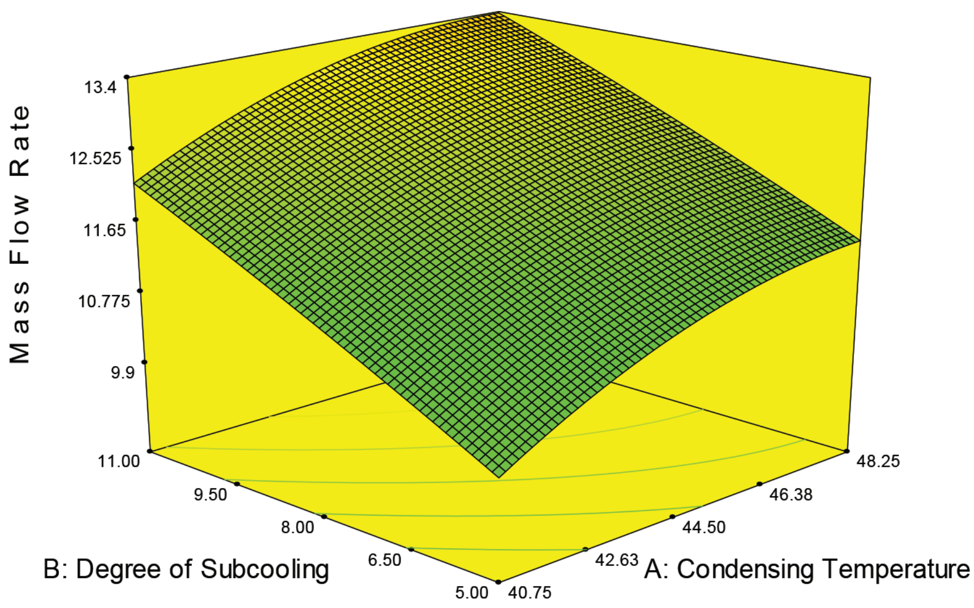


Fig.4. A 3-D graphical surface plot of mass flow rate versus degree of subcooling and condensing temperature

Fig.5 shows the 3-D graphical surface plot of mass flow rate for capillary tube length and diameter. It can be clearly seen in the figure that the mass flow rate increases with the increase in tube diameter and also increases with a decrease in tube length. This may be due to the fact that in a shorter capillary tube length, there is a smaller effect of wall frictional force on the refrigerant.

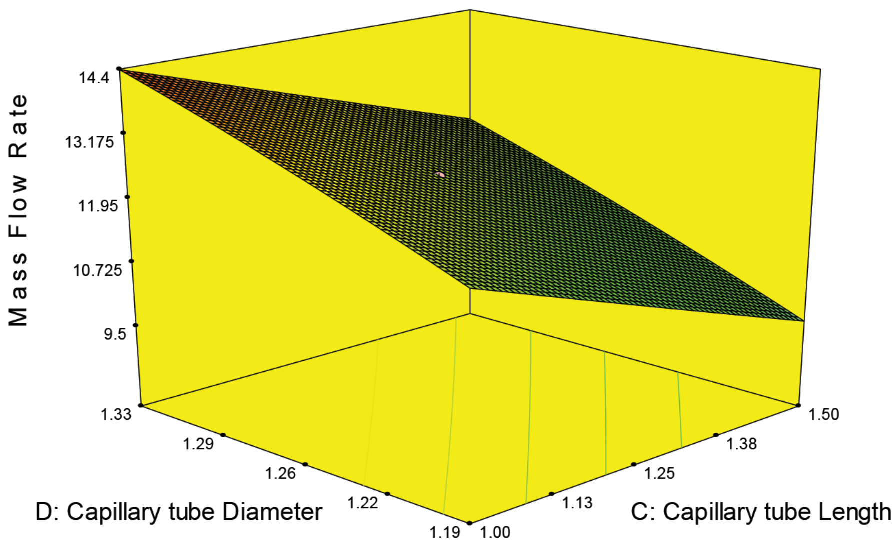


Fig.5. A 3-D graphical surface plot of mass flow rate versus capillary tube diameter and length

## CONCLUSION

An experimental statistical design of response surface methodology has effectively been used in planning, analyzing and optimizing the four independent factors and assessing their effects on the response variable - refrigerant mass flow rate. The mass flow rate correlation of refrigerant HFC407C/HC600a/HC290, a new refrigerant mixture developed, showed that the mass flow rate strongly depends more on capillary tube length and diameter. In addition, the reliability and adequacy of this empirical correlation were also evaluated using the analysis of variance (ANOVA) and the results showed that this model had given a good estimation of measured refrigerant mass flow rate. The average deviation between the calculated mass flow rate and the measured was about – 1.05%. Based on the results of these comparisons, it can be concluded that, for cost effectiveness, statistical experimental design approach is an effective tool for developing refrigerant mass flow rate in capillary tubes. Though the empirical correlation developed in this study is in good agreement with the measured data and previous correlation, it should be applied for the specified refrigerant of this study.

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