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Empirical Correlation Of Refrigerant R-22 Mass Flow Rate Through Adiabatic Capillary Tube Using Statistical Experimental Design

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Abstract

A capillary tube is an expansion and metering device used in small vapor compression refrigeration systems such as household refrigerators and freezers. This paper presents a new empirical correlation for predicting refrigerant R-22 mass flow rate through adiabatic capillary tube using central composite design. The correlation is based on the previous researches that say the mass flow rate depends on four major parameters, namely the length of capillary tube, inner diameter of capillary tube, condenser temperature and degree of sub cooling. In the present study, the experimental data of the capillary tube covers capillary tube length ranging from 0.75 to 1.75 m, inner diameter from 1.11 to 1.40 mm, condensing temperature from 37 to 52^{o}C and degree of sub cooling from 2 to 14^{o}C.The correlation was tested with analysis of variance of 5% level of significance and the result showed that the equation model fitted well with the experimental data.

***Keyword**: Capillary tube, household refrigerator, R-22, empirical correlation*

1. Introduction

Capillary tube is a small bore tubes used as expansion and metering device in small vapor compression refrigeration system such as household refrigerators and air-conditioners. It is a drawn copper tube with diameter ranging from 0.5 to 2mm and length from 1.5 to 6m. The capillary tubes offers quite a number of advantages over the other expansion device like thermostatic and thermocouple expansions device such as its simplicity, inexpensive, and required low starting torque for compressor (Bansal and Rupasinghe, 1996)

Though, the capillary tube has a simple geometry, the refrigerant flow in the tube is complex and the mass flow rate along the tube has a strong influence on the performance of the refrigeration system. In the last 50 years, many studies have investigated the performance of adiabatic capillary tube. Some have presented theoretical model using mathematical approaches based on numerical simulations for the refrigerant flow in the capillary tube. In these studies, most of them divided the refrigerant flow in capillary tube into subcooled single-phase and two-phase liquid-vapor thermodynamic equilibrium regions (Bansal and Rupasinghe, 1998, Sami and Tribes, 1998). The two-phase flow has been generally simplify to be homogeneous two-phase where it is assumed that no slip occurs between the phases (the two phases move with the same velocity). For example, Bansal and Rupasinghe (1998) developed a two-phase homogeneous model which they termed 'CAPIL'. The mass, energy and momentum conservation equations were solved simultaneously using iterative procedure and Simpson's rule. Another approach employed is the separated flow model approach where the slip that existed between the liquid and vapor is considered and a mixture variable called void fraction is introduced to the conservation equations. For instance, Wongwises and Chan (2000) used separated flow model to compare various two-phase friction correlations and slip ratio correlations. They applied the conservation of mass, momentum and energy equations to obtain sets of partial differential equations which were solved using fourth order Runge-Kutta method. The last model that is often used to study the behavior of refrigerant flow in capillary tube is the drift flux model where the entire two-phase liquid-vapor mixture is considered when formulating the conservation equations (Liang and T.N.Wong, 2001).

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, Yilmaz and Unal (1996) presented an approximate analytic solution. In their study, the reference point was not correctly chosen, as a result, the choked condition at the exit of the capillary tube was ignored which lead to some wider deviation in result in their calculations. In an attempt to solve this problem, Ding et al. (1999) and Zhang and Ding (2001) analyzed the work of Yilmaz and Unal (1996) and gave some modification. Though, the modified model gave a good agreement with the existing numerical models, however, the consideration of the choked flow caused iterative calculation, as a result, the approximate analytic model is still not an explicit solution yet.

On like 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., 2003, Kim et al., 2002, Melo et al., 1999, Augusto Sanzovo Fiorelli et al., 2002, Zhou and Zhang, 2006, Park et al., 2007). A simple correlation for sizing adiabatic and non-adiabatic capillary tubes were presented by Bansal and Rupasinghe (1996). They combined both the operating and geometric parameters to develop the mass flow rate empirical correlation. In their study, refrigerant properties were not considered. However, Bittle et al. (1998) considering the refrigerant properties, developed a generalized correlation with dimensional analysis method. In their study, experimental data for subcooled and two-phase flow with refrigerants R-22, R-134a, and R-410A was applied. Melo et al. (1999) performed an extensive experimental study using refrigerant R-12, R-134a, and R-600a and developed some empirical correlations for each of these refrigerants.

Straight and coiled capillary tubes empirical correlations with refrigerants R-22, R-407C, and R-410A were also developed by Kim et al. (2002) using Buckingham pi theorem. In the work of Choi et al. (2003, 2004), the existing dimensionless parameters were modified and new general empirical correlation was developed. There are differences when comparing the new coefficients and exponents with the previous correlations. These might be due to the fact that different experimental data were used when developing the correlations. Furthermore, artificial neural network was used to develop dimensionless empirical correlation for subcooled inlet condition using experimental data of R-12, R-290, R-600a, R-134a, R-407C, R-22, and R-410A (Zhang, 2005). Recently, Vins and Vaceks (2009), presented experimental investigation on two-phase flow in capillary tube using R-218 refrigerant. Two correlations were developed using two approaches: conventional Buckingham pi theorem and artificial neural network (ANN) approach. Comparing the two approaches, the average and standard deviation for Buckingham pi theorem correlation gives -0.41% and 4.85% respectively while the ANN correlation gives -0.12% and 3.45% respectively.

All the empirical correlations mentioned above do not use statistical experimental design to investigate the behavior of refrigerant flow in capillary tube in order to develop their correlations. Statistical experimental design are economical because it requires relatively small number of experiment and yet able to be analyzed by statistical methods resulting in a valued conclusion. This approach of experimental design is very important if meaningful conclusions were to be drawn from the data. Statistical approach is the only systematic and scientific approach to analyze data when problem that involve experimental errors are considered (Montgomery, 2005).

Very few researchers (Bittle and Pate, 1996, Bittle et al., 1995, Melo et al., 2002) have applied statistical experimental design to develop an empirical correlation to predict the refrigerant mass flow rate in capillary tubes. Melo et al. (2002) performed an experiment using statistical factorial design of experiment on concentric diabatic capillary tube with R-600a 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 these studies are still very limited. Refrigerant R-22 is the most common refrigerant used as working fluid in capillary tube refrigeration systems. The objective of this paper is to develop an empirical correlation with another refrigerant (R-22) that can be use 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.

2. Development of Correlation

As described above, the refrigerant mass flow rate in capillary tube depend on the length of capillary tube (L), inner diameter (D), condenser 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, however, the effects of these properties have been to some extent taken care of by condenser temperature and degree of subcooling. In order to reduce the experiment to be performed, which is the main advantage of this approach, statistical technique, central composite design (CCD) was used to construct the test matrix. A four factor CCD with one replicate at the centre point was employed in designing the experimental test. The total experimental run that will be required to complete the experiment is 25. The constructed matrix is based on two-level of alpha – low and high level. The lowest and highest values of each of the design parameter were input into the Design expert software (version 7.1, Stat-Ease, Inc., Minneapolis, USA). Thereafter, the software generated the experiment to be performed. The ranges and level of factors used are shown in Table 1.

Table1. Experimental range and level of central composite design

Variables	**Range and levels**					
	-2	-1	0	1	2	-2
Condenser temp. (°C)	37.00	40.75	44.50	48.25	52.00	37.00
Degree of Subcooling (°C)	2	5	8	11	14	2
Length of tube (m)	0.75	1.25	1.00	1.50	1.75	0.75
Diameter of tube (mm)	1.118	1.1800	1.1878	1.2575	1.3000	1.118

3. Resuts 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 of the design parameters generated from the software, the responses were carefully selected from the experimental data of Jabaraj et al. (2006). The result is shown in Table 2.

In order to obtain optimum mass flow rate through the adiabatic capillary tube, the optimization procedure of Design Expert, the regression formulated by the software relating the responses to the factors need to be examined. The generated multiple regression empirical correlation equation for refrigerant mass flow rate is given in equation 1.

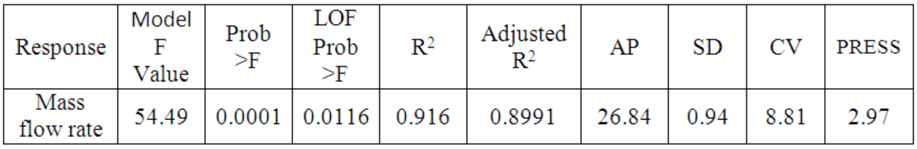
$$m_{emp} = -27.60397 + 0.24249T_{cond} + 0.36422\,T_{sub} - 5.18689L + 25.31331D \qquad (1)$$

Table2. CCD response result for four parameters

RUN	**CONDENSER TEMPERATURE (^{O}C) – factor 1**	**DEGREE OF SUBCOOLING (^{O}C) – factor 2**	**CAPILLARY TUBE LENGTH (m) – factor 3**	**TUBE INNER DIAMETER (m) –factor 4**	**MASS FLOW RATE (kg/s) - response**
1	37.00	2.00	0.75	1.1180	7.67
2	37.00	5.00	1.50	1.1800	5.19
3	37.00	5.00	1.25	1.3970	11.12
4	37.00	8.00	1.25	1.2700	9.71
5	37.00	11.00	1.75	1.2700	8.85
6	48.25	5.00	1.50	1.1878	7.84
7	44.50	8.00	0.75	1.2575	13.5
8	*40.75*	*11.00*	*1.00*	*1.3273*	*14.4*
9	48.25	5.00	1.00	1.1878	10.29
10	40.75	5.00	1.50	1.3273	10.03
11	44.50	2.00	1.25	1.2575	9.3
12	40.75	11.00	1.50	1.1878	8.37
13	52.00	8.00	1.25	1.2575	12.16
14	40.75	11.00	1.00	1.1878	9.45
15	40.75	11.00	1.50	1.3273	12.35
16	40.75	5.00	1.00	1.3273	11.91
17	44.50	14.00	1.25	1.2575	13.72
18	48.25	11.00	1.50	1.3273	15.11
19	40.75	5.00	1.50	1.1878	6.08
20	37.00	8.00	1.25	1.2575	9.71
21	48.25	11.00	1.00	1.3273	18.1
22	40.75	5.00	1.00	1.1878	9.47
23	48.25	11.00	1.50	1.1878	9.19
24	44.50	8.00	1.25	1.1180	8.89
25	44.50	8.00	1.25	1.2575	13.17

The Analysis of Variance (ANOVA) for the empirical correlation model is summarized in Table 2. 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 actual points from the fitted surface, relative to pure error (Anderson and Whitcomb, 2005). Preferable is the large value of Prob>F for LOF which is greater than 0.05. For 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 and Whitcomb, 2005). The AP that exceeds 4 usually indicates that the model will give reasonable performance in prediction. PRESS, is the prediction error sum of squares and 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).

Table2. 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	54.49	0.0001	0.0116	0.916	0.8991	26.84	0.94	8.81	2.97

The empirical correlation regression model (Eq.1) is a significant model since its Prob>F value is less than 0.05. The Prob>F for LOF is large and this means that the LOF of the model is insignificant. In addition, the SP, AP and PRESS for the regression model are satisfactory since the AP is more than 4 and SD and also PRESS values are small as shown in Table 2

Figure 1 compares the experimental data of refrigerant with the predicted mass flow rate obtained from equation 1. A practical thump rule for evaluating determinant coefficient R^2 is that it should be at least 0.75 or above. The value of R^2 for the predicted mass flow rate model is 0.9160 showing that the model is adequate to explain most of the variability of the experimental data. The absolute deviation or difference between the calculated mass flow rate and the measured is less than 1.05 kg/s.

The effects of condenser temperature and degree of subcooling on mass flow rate of refrigerant are represented in three dimensional contour plots shown in Fig. 2. It should be noted that the optimum points can be found within the experimental region in the Figure. As a result, it can be concluded that all the experiments were conducted in the optimal region and optimum mass flow rate should not lie beyond the experimental range.

4. Conclusion

Empirical correlation to predict the refrigerant mass flow rate through adiabatic capillary tube was derived from experimental data using statistical experimental design. The absolute mean deviation error for the refrigerant mass flow rate was 1.05kg/s. The results of this investigation show that the empirical correlation to estimate refrigerant flow in an adiabatic capillary tube can be applied to condition outside the range covered by this central composite design. It is hoped that the propose correlation will be a good tool for capillary tube designers modeling HCFC-22 refrigeration system.

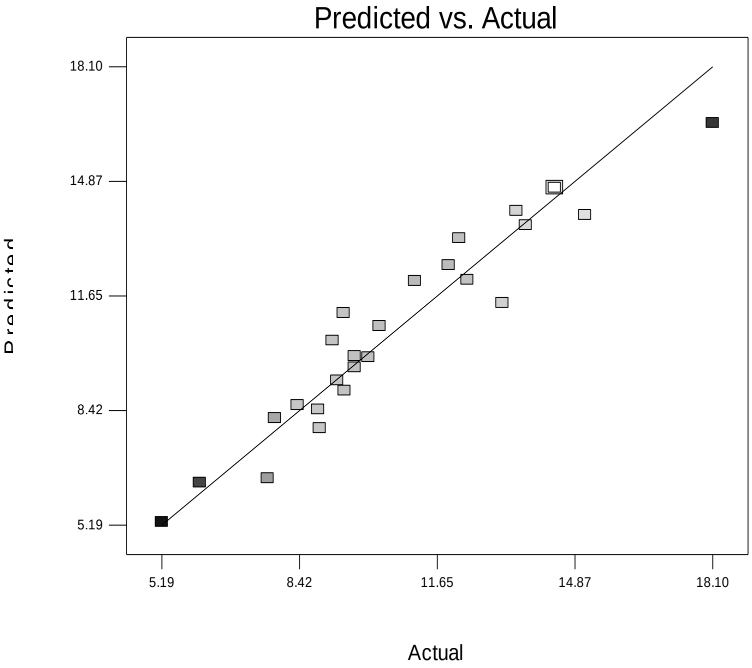


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Figure1. Predicted vs. actual values plot for refrigerant mass flow rate

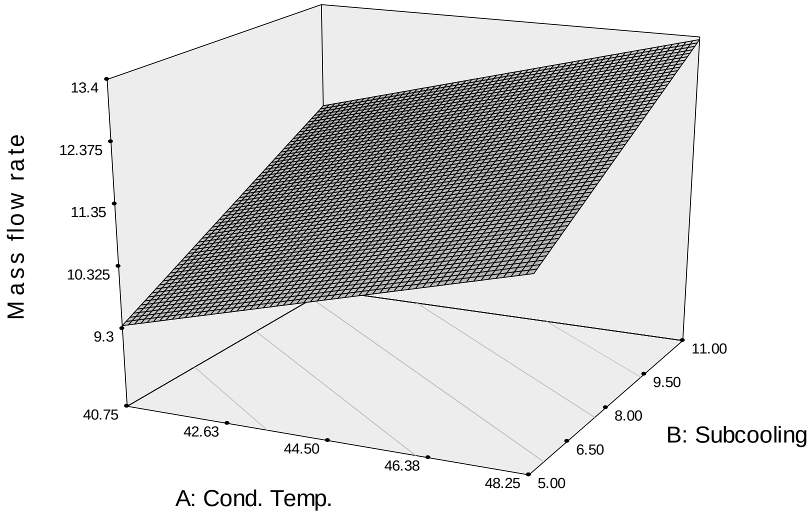

Figure2. The response surface plot of mass flow rate as function of condenser temperature and subcooling

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