A PREDICTION MODEL FOR ADIABATIC AND DIABATIC CAPILLARY TUBES WITH ALTERNATIVE REFRIGERANTS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2014

Major Subject: Mechanical Engineering

ABSTRACT

The capillary tube is a very common throttling device located between the condenser and evaporator in a refrigeration system. In some refrigerant systems, a section of the capillary tube is connected to a section of the vapor return line (suction line) that exits the evaporator, which creates the so called capillary tube/suction line heat exchanger. Models to predict the mass flow in both adiabatic capillary tubes and capillary tube/suction line heat exchangers are developed in this thesis.

In order to predict the refrigerant mass flow in adiabatic capillary tubes and in capillary tube/suction line heat exchangers, a number of dimensionless correlations are developed. These dimensionless correlations are regressions of dimensionless parameters based on geometry factors, condition effects, and fluid properties, which are generated from the Buckingham Pi Theorem. The correlations for the mass flow of each individual refrigerant (R-134a, R-22, R410a) in the adiabatic capillary tubes were generated, as well as for each refrigerant (R-134a, R-22, R410a, R600) in the capillary tubes/suction line heat exchangers. The average deviations of the specific refrigerant correlations range from 1.27% to 6.30% for both the adiabatic capillary tube and heat exchanger. The deviation of the generalized correlation is 1.91% for adiabatic capillary tubes with subcooled inlet conditions, 4.89% for adiabatic capillary tube with quality inlet conditions, and 2.47% for heat exchangers with subcooled inlet condition. These newly developed correlations developed in this thesis can provide more accurate predictions for mass flow in both adiabatic capillary tubes and capillary tube/suction line heat exchangers when compared to the old correlations published in ASHRAE reports and Handbooks.

Generalized correlations with a reduced number of pi-terms were developed to predict the refrigerant mass flow. This simplification study shows that the accuracy is stable when the pi-term number is higher than 4 for adiabatic capillary tube simulations, and 5 for capillary tube/suction line heat exchangers.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Michael B. Pate for his guidance, support, and for imparting his knowledge and experience to me throughout this research study. I also sincerely appreciate Dr. Bryan Rasmussen and Edward B. White for their serving on my thesis committee. Finally, I would like to thank to my mother and father for their support and encouragement.

NOMENCLATURE

Cp	Specific heat (Btu/lbm-°R)
D	Diameter (in)
h	Enthalpy (Btu/lbm)
L	Length (in)
$\dot{m}$	Mass flow rate (lbm/h)
P	Pressure (psia)
T	Temperature (℉)
x	Quality
μ	Dynamic Viscosity (lbm/ft-h)
π	Dimensionless parameter
σ	Surface tension (lbf/ft)
ν	Specific volume (ft^3/lbm)
c	Capillary
capin	Capillary inlet
f	Liquid saturation
g	Vapor saturation
hx	Heat exchange
i	Inlet
fg	Vaporization
s	Saturation/Suction

sc	Subcool
sh	Superheat
suctin	Suction inlet

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CHAPTER I

INTRODUCTION

1.1. Background

Capillary tubes used within refrigeration systems are not related to capillary action. The capillary tube is a common throttling device located between the condenser and the evaporator in a refrigeration system. It is simply a copper tube with a small internal diameter. The internal diameter of the typical capillary tube varies from 0.02 inches (0.51mm) to 0.09 in (2.29mm) with varying lengths from 20 inches (508mm) to 200 inches (5080mm). In some refrigerant systems, a section of the capillary tube is connected to a section of the vapor return line that exits the evaporator (suction line), which creates the so called capillary tube/suction line heat exchanger. Generally, the length of the heat exchanger is shorter than the capillary tube. An adiabatic upstream capillary tube and an adiabatic downstream capillary tube exists in a capillary tube/suction line heat exchanger.

The simple design of capillary tubes makes them the main expansion device used in small refrigeration systems and more popular than other expansion devices. Also, both the manufacturer and the customer benefit from the lower cost of this simple design. In addition, the system pressures can equalize during “off-cycle” periods and as a result, the compressor starting torque demands can be decreased.

The adiabatic capillary tube links the evaporator and the condenser in the refrigeration system as shown in Fig.1.1. A capillary tube/suction line heat exchanger allows the thermal energy to be transferred from the capillary tube to the suction line as shown in Fig.1.2. The system can operate at the design conditions due to the appropriate restrictions provided by the capillary tube. Under normal circumstances, the refrigerant entering the capillary tube is subcooled liquid and the refrigerant pressure reduces linearly due to friction. Then however, the refrigerant will start to vaporize, or flash, when the refrigerant pressure drops below the saturation pressure. The point starting the vaporization is normally referred to as the “flash point”.

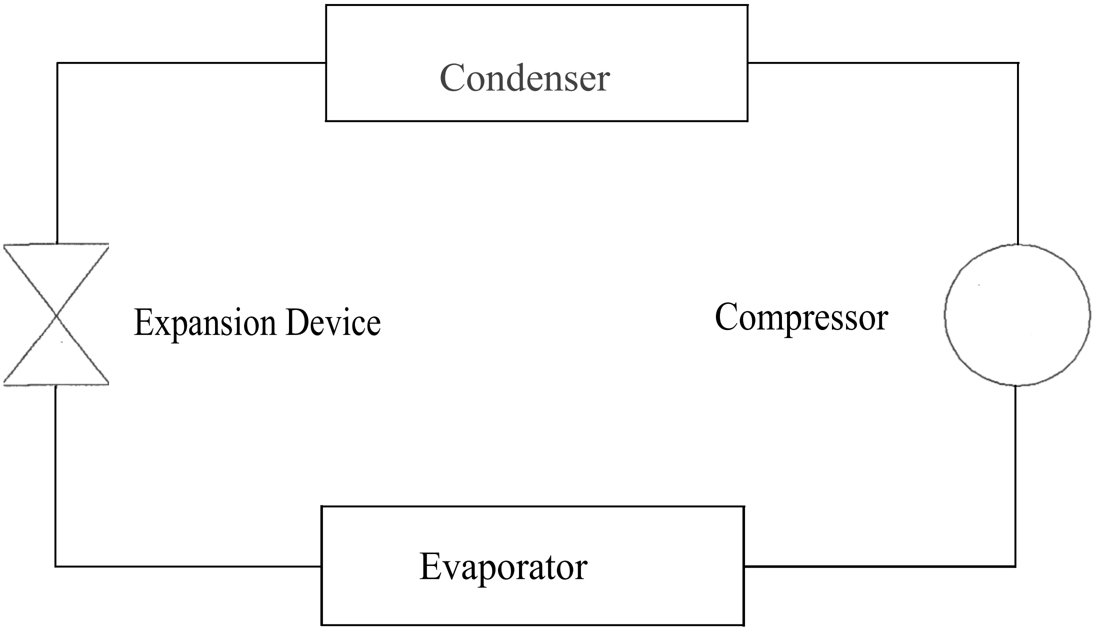

Figure 1.1 Typical Refrigeration System Configuration

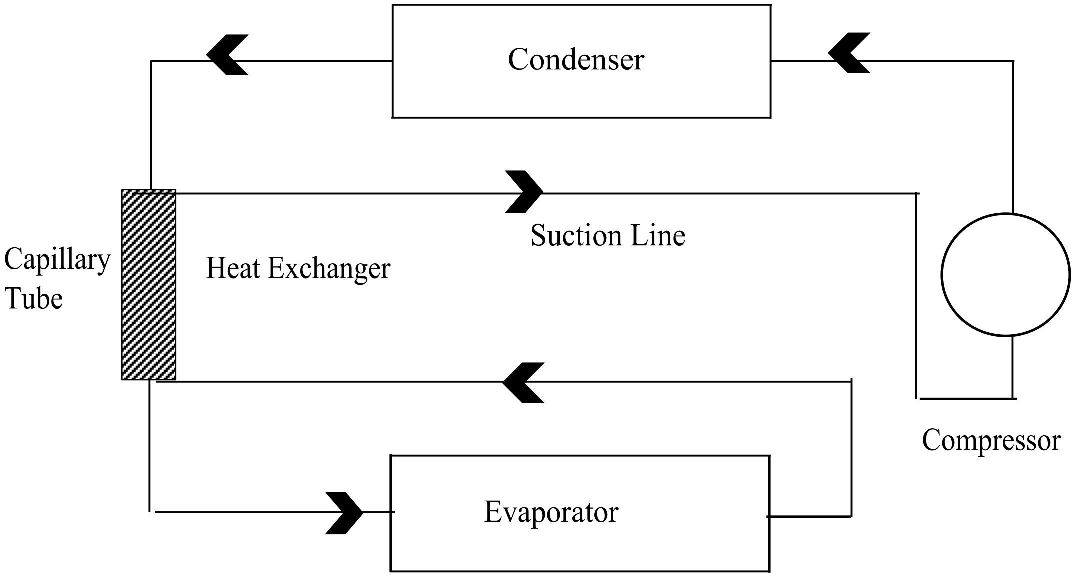

Figure.1.2 Schematic of Refrigeration Cycle with Capillary Tube/Suction Line Heat Exchange

The vapor acceleration and two-phase friction cause the refrigerant pressure to drop quickly after the flash point. Because the refrigerant is saturated after the flash point, the saturation temperature will decrease due to the pressure drop and the quality of the refrigerant will increase. Normally, the refrigerant is a choked fluid at the end of the capillary tube.

Compared to adiabatic capillary tube systems, capillary tube/suction line heat exchangers have two primary benefits. First, the refrigeration system capacity for a given refrigerant mass flow increases due to the thermal energy transfer from the capillary tube. Second, the heat transferred to the refrigerant vapor in the suction line guarantees that vapor returns to the compressor and avoids compressor slugging.

1.2. Motivation

The mass flow prediction equation for adiabatic capillary tubes contained in the ASHRAE Handbook is based on the research of Wolf et al. (1995), while the mass flow prediction equation for capillary tube/suction line heat exchangers is based on the research of Wolf and Pate (2002). These prediction equations were developed by correlating experimental data along with tube geometries and refrigerant properties. Considering the fact that these correlations were developed over ten years ago, refrigerant property data available from the National Institute of Standards and Technology (NIST) for alternative refrigerants have been updated and in some cases the changes are significant. Therefore, a need exists to replace the original property data with updated property data to develop new equations for accurately predicting the mass flow of refrigerants though adiabatic tubes and capillary tube/suction line heat exchangers. Because the existing capillary tube design procedures are based on equations developed with the original property data, updated equations based on updated property data are needed to revise the design procedures in the ASHRAE Handbook.

The purpose of this study is to use updated refrigerant properties to develop accurate correlations based on for predicting refrigerant mass flow through adiabatic tubes and capillary tube/suction line heat exchangers. These correlations are based on device geometry and refrigerant properties for a variety of alternative refrigerants.

CHAPTER II

LITERATURE REVIEW

2.1. Introduction

A literature study of the performance of refrigerant mass flow in capillary tubes is presented. The materials include adiabatic capillary tubes as well as capillary tube/suction line heat exchangers, which refers to the diabatic capillary tubes. Over 60 years of research and study have been devoted to capillary tubes, leading to a huge collection of literature. There have been numerous past attempts to accurately predict the refrigerant mass flow rates through capillary tubes, while alternative refrigerants are the current topics of capillary tube research. The past literature was reviewed in detail for the period 1946 to 2000 for both adiabatic and diabatic capillary tubes in “Capillary Tube/Suction Line Heat Exchangers Performance with Alternative Refrigerants” 948-RP ASHRAE Final Report 2002, by D. A. Wolf and M. B. Pate. An additional literature survey for the past fourteen years is necessary to understand the research history for capillary tubes. This literature review can be divided three parts: a literature survey of experiments, a literature survey of numerical simulations, and a literature survey of prediction models.

2.2. Literature Survey of Experimental Studies

In this section, experimental studies of the performance of capillary tubes from 1948 to 2013 are reviewed.

Bolstad and Jordan (1948) were the first to measure CFC-12 temperatures and pressures in capillary tubes. They also tested a capillary tube/suction line heat exchanger with HFC-22. The measured flow rates with capillary tube diameters, lengths, and inlet pressures were plotted. Swart (1946) was the first researcher to show that the refrigerant has a linear pressure drop in the subcooled situation and an exponential pressure drop in the two-phase situation. Swart's research included both capillary tube/suction line heat exchangers and adiabatic tubes. Marcy (1949) developed a method to select capillary tubes; CFC-12 and SO2 were used for this research. The experimental results were in agreement with the predicted results.

Pasqua (1953) was the first to find the occurrence of metastable flow for refrigerants. Mikol (1963) presented a capillary tube investigation of friction factors, flow models, and choked conditions. They found "drawn copper tubing of a small bore cannot be considered smooth for purposes of friction factor selection". Mikol and Dudley (1964) observed that vaporization in glass tubes occurred only at one point. Christenson and Jorgensen (1969) presented capillary tube/suction line heat exchanger tests. A brine solution was used for heat transfer, which was contrasted with the usual method of soldering the two faces.

Koizumi and Yokoyama (1980) confirmed Cooper and Mikol's observations of homogeneous flows, R-22 was used in their study. Pate and Tree (1983-1987) published several studies of capillary tube/suction line heat exchangers. A computer model to calculate the mass flow in capillary tubes was published in the first paper (1983). Simultaneous solutions of four differential equations were required for this model. The second paper (1983) described more details of the experimental results. The flow rates in the heat exchanger increased 20% over the adiabatic tube.

Li et al. (1990) presented a research of metastable flows of CFC-12, where metastable flow characteristics in capillary tubes were measured. A chart showed that the under pressure of vaporization and the metastable fluid length decreased, when the diameter increased. A pressure drop examination of CFC-12 in the adiabatic capillary tube was presented by Lin et al. (1991). Based on the examination data, the roughness of the capillary tube wall had an obvious effect on the coefficient of frictional pressure drop. A model to predict the frictional pressure drop was also presented. Melo et al. (1994) presented an experimental data of CFC-12 and R-134a mass flows in capillary tubes. Effects of subcooling degree, capillary tube diameters, and capillary tube lengths were discussed. The application of capillary tube/suction line heat exchangers in the refrigeration cycle was accessed by Domanski and Didion (1994). The capillary tube/suction line heat exchangers had a significant influence for the system performance. COP increased for R134a, R600a, and R152a, but decreased for R22.

Bansal et al. (1996) evaluated the effect of capillary tube length, heat exchanger length and entrance length for the capillary tube/suction line heat exchanger. The study concluded that the refrigerator power consumption was not affected by any single variable, and that the combination of a short capillary inlet length, a long capillary tube length and a long heat exchanger length provided the best result. Chang and Ro (1996) also performed a study for the pressure drop in the adiabatic capillary tube. HFC-32, HFC-125, R-134a and their mixtures were used as working fluids. They concluded that a tube’s relative roughness has a significant effect on the refrigerant pressure drop even though the absolute value was very small. The experimental results reported by Meyer and Dunn (1998) showed that the discontinuities occured in mass flow rate measurements with the subcooling inlet levels, while the varied inlet conditions resulted in different mass flow rate paths. Experimental studies of adiabatic capillary tubes with R407C and R22 was performed by Wei et al. (1999). The measured data was compared with the predicted mass flow and a new correlation was developed for R407C.

The hysteresis effects on capillary tube/suction line heat exchangers were studied by Liu and Bullard (2000). Discontinuities in the measurements of mass flow were also observed in their study.

Melo et al. (2002) published an experimental study for capillary tube/suction line heat exchangers with R-600a which resulted in a16-point data file. Empirical correlations were generated to predict the mass flow rate and the outlet temperature of the suction line based on these results. The mean deviation for mass flow rate and outlet temperature was 0.07 kg/h and 0.6℃, respectively.

Kim et al. (2002) presented experimental results of adiabatic tubes for R22, R407C, and R410A; both straight and coiled tubes were contained in this study. The mass flows in coiled capillary tubes were lower than those in straight capillary tubes. A dimensionless prediction correlation was also presented with a deviation between -12% and +12%. The prediction results agreed with the data in the open literature. An experimental study for R407C and R410A through adiabatic capillary tubes was published by Fiorelli et al. (2002). The effect of inlet and outlet conditions and the effect of geometries were analyzed in this paper. The performance difference between R407C and R410A was also performed; but prediction models were not given.

Jabaraj et al. (2006) presented an experiment study for a HFC407C/HC600a/HC290 refrigerant mixture in adiabatic capillary tubes. The mass flow rates of HCFC22 and HFC407C/HC600a/HC290 refrigerant mixtures in adiabatic capillary tubes were measured with different inlet conditions and geometries in this study. Based on this data, a dimensionless prediction correlation was developed. The predicted mass flow was in good agreement with the measured mass flow.

Park et al. (2007) performed a study of coiled capillary tubes. The R22 mass flow rates were measured for both the straight tubes and the coiled tubes at various geometries and operating conditions. The mass flow rates in coiled capillary tubes were 5%-16% lower than those in straight capillary tubes at the same conditions. A prediction correlation was also created based on the database from previous literatures. This correlation presented good accuracy for both coiled and straight capillary tubes.

Khan et al. (2008) presented an experimental study for adiabatic spiral coiled capillary tubes with R-134a. The experimental results showed that the mass flow in coiled capillary tubes was reduced 5%-15% compared to those in straight capillary tubes; a correlation was also developed based on the experimental data. It was also found that 91% of the predicted mass flow was in an error band of ±10%. Khan et al. (2009) [9] also published an experimental study for diabatic flow of R-134a through spiral capillary tubes. An empirical correlation was also developed for diabatic flows with a deviation of 7%.

2.3. Literature Survey of Numerical Simulations

Numerical simulations of the performance of capillary tubes are surveyed in this section.

Rizza(1982) developed a numerical model to predict refrigerant mass flows that contained subcooled liquids, bubble flows, Slug flows, and mist annular flows. All of the predicted mass flow rates were within a 5% band.

Pate and Tree (1986) plotted capillary tube data on thermodynamic state paths and compared two-phase viscosities. A numerical model of capillary tube/suction line heat exchangers with subcooled inlet conditions was presented in another paper by Pate and Tree (1986). The model result was in good agreement with the experimental data. Pate and Tree (1987) verified choked flow conditions at the capillary tube exit, and a variety of models of mass flows with choked two-phase conditions were compared.

Li et al. (1991) published a numerical model for the whole capillary tube. Horizontal, adiabatic, steady flows were the assumption of this model, but only comparison plots of pressure were presented. Chen et al. (1991) presented plots of quality, the relative drift velocity and the void fraction, although no experimental data was presented.

Dirik et al. (1994) published an experimental study of R-134a for adiabatic and diabatic tubes, and a numerical model was developed. The prediction flow rates were within 10% of the experimental flow rates.

Wong et al. (1994) developed a numerical model for homogeneous flow, and the Dukler two-phase viscosity relationship was incorporated into the model.

A numerical method to simulate Fanno flows of refrigerants in capillary tubes was developed by Chung (1998). Pressure has been used as an independent variable in traditional methods, while it was used as a dependent variable in this simulation. Wongwises and Suchatawut (2003) presented a numerical model to simulate the performance of refrigerant flows through adiabatic capillary tubes. The metastable flow region was simulated and annular flow was considered to happen in the two-phase region. This model was proved valid by comparing with experimental data in the published literature.

Fiorelli (2003) compared the homogeneous flow model and the separated flow model for capillary tubes with refrigerant mixtures. The prediction results were compared with R-410a and R407c experimental data. The study indicated that both models were suitable to predict the refrigerant mixture flow in capillary tubes

Zhang and Ding (2004) developed a numerical model to measure the length of adiabatic capillary tubes as well as a numerical model to predict the mass flow in adiabatic capillary tubes. Both choked and non-choked flow conditions were taken into account.

Yang and Bansal (2005) presented a numerical model for capillary tube/suction line heat exchangers and analyzed the effect of different geometries and operating conditions. They found that a condition of 3K of subcooling and 1.4–1.6 m of heat exchanger length was the best design point for capillary tube/suction line heat exchangers.

Hermes et al. (2008) developed a simplified numerical model to simulate the mass flow in capillary tubes. The simplification of this model improved numerical stability and computation speed. Large amounts of experimental data were used to verify this model and the result was that 91.5% of the predicted flow rates for adiabatic tubes and 79.3% for non-adiabatic tubes were in a ±10% error band.

Hermes et al. (2010) developed an algebraic model to predict the mass flow in adiabatic capillary tubes. A series of relatively simple thermodynamic equations were used to formulate this model, and experimental data for R-134a and HC-600a were used to verify this model with error bands being between ±10% to ±15%. In the same year, Hermes et al. presented a second paper containing an algebraic model to predict the mass flow in the capillary tube/suction line heat exchangers. Both numerical and empirical correlations from previous researchers were included in this model.

Reference data for heat exchangers was generated by Sarker and Jeong (2012) by using a numerical mechanistic model rather than experimental data.

Sulaimon et al. (2012) presented a homogenous mass flow prediction model for adiabatic capillary tubes. In order to improve the prediction accuracy, the initial vapor quality was used to predict the onset of vaporization in the capillary tube. The inlet conditions of the capillary tubes were also included, and the resulting model had a reasonable accuracy.

2.4. Literature Survey of Mass Flow Prediction Models

Models to predict the mass flow in capillary tubes from 1948 to 2013 are reviewed in this section.

Lathrop (1948) found some rough functional relationships between parameters and mass flow in capillary tubes; however, they could not be used for calculations. The relationships were available for CFC-12 and R-22. The ASHRAE design charts developed by Hopkin (1950) had two sets of graphs for CFC-12 and R-22. Prosek (1953) also plotted a set of design charts individually for CFC-12 and R-22. Cooper et al. (1957) developed a Fanno line flow model, which later proved that the plot of the Fanno line pressure against the specific volume on semi-log paper was a straight line; they also observed the delay of vaporization.

Rezk and Awn (1979) developed rating charts for CFC-12 mass flows in capillary tubes. The flow rate increased with the degrees subcooling decreased flashing temperature. Maczek and Krilicki (1983) presented a model for bubbled flows through capillary tubes. This model was an improvement of the homogeneous model, but more research was necessary. The influence of thermal non-equilibrium for mass flow in capillary tube was studied by Kuiper and Janssen (1983). A correlation of capillary inlet temperatures and mass fluxes was attempted. A temperature and pressure analysis for capillary tube/suction line heat exchangers was published by Pate and Tree (1984). They hypothesized that the flow rate in the heat exchanger increased because the heat transfer suppressed the quality in the two-phase region. The latter paper published by Pate and

Tree (1984) included a linear quality model of heat exchangers that used the two-phase region.

A prediction correlation for the metastable flow of CFC-12 was presented by Li et al. (1990) and Chen et al. (1991). The correlation was applied over a narrow range of diameters from 0.026 in to 0.046 in. Paiva et al. (1994) also presented a model for capillary tubes and predicted flow rates were approximately 10% less than measured flow rates. A capillary tube/suction line heat exchanger model was developed by Peixoto and Bullard (1994). A comparison showed the lateral arrangement had a much greater flow than a concentric arrangement. Based on the data from the open literature, Escanes et al. (1994) generated a selection chart for CFC-12, HCFC-134a and R-22 but no comparisons were presented. Bittle et al. (1995) developed a mass flow prediction correlation for R-152a in capillary tube/suction line heat exchangers. This correlation was also used in determining the effective subcooling level. All the points were in the ±10% error band, while the mass flow rates of CFC-12 predicted by this correlation were 20% lower than measured mass flow rates. Bittle et al. (1995) compared experimental mass flow rates and effective subcooling levels of CFC-12 with the data predicted by the previous ASHRAE Handbook. They concluded that the ASHRAE method to predict the mass flow in adiabatic capillary tubes was not accurate, but it was valid to predict the mass flow in capillary/suction line heat exchangers. Melo et al. (1995) presented an experiment for R600a, R134a, and R-12 in adiabatic capillary tubes. The observation showed that the pressure tap did not initiate disturbances in the flash point inception. A prediction correlation was also performed for the single-phase friction factor. Escanes et al. (1995) presented a one-dimension model for capillary tubes. The elements governing this model included mass continuity, energy, entropy creation and momentum.

Bansal and Rupasinghe (1996) formulated a model to calculate adiabatic and non-adiabatic tube lengths. The predicted mass flow was compared with the measured data with the deviation falling within ±9% for both tubes. Bittle and Pate (1996) performed a correlation to predict the mass flow and effective subcooling level of R-134a. Some data points of R-152a and CFC-12 were used to verify this correlation. Chang and Ro (1996) developed an empirical model for HFC-32/134a, HFC-32/125, and HFC-32/125/134a with a 10% difference between the model prediction and published data.

Nezavilla and Melo (1996) developed a homogeneous model to predict the mass flow in non-adiabatic capillary tubes. Experimental data of R-134a from Dirik et al. (1994) and CFC-12 from Bittle et al. (1995) were used for comparison. They also found that the mass flow rate decreased when the heat exchanger was shifted further down the capillary tube. Seixlack et al. (1996) formulated a two-fluid model to simulate the R-134a performance in adiabatic capillary tubes. Five conservation equations were included in this two-fluid model, which was a more accurate presentation of the flow in the capillary tube. Wong and Ooi (1996) used a theoretical model to evaluate CFC-12 and R-134a performance in adiabatic capillary tubes. They concluded that the pressure drop for CFC-12 was less than that for CFC-12 in both the liquid and two-phase sections. Wong and Ooi (1996) also reported that both the separated flow model and the homogeneous model properly predicted the mass flow through capillary tubes.

Bittle et al. (1998) presented a general model to predict the mass flow in adiabatic capillary tubes. This was the first empirical model to include both tube geometries and refrigerant properties. R134a, R22 and R410a were used to develop this model. Chen et al. (1999) presented rating charts for R-134a mass flow through adiabatic capillary tubes with geometrical and operating elements were used as the rating charts variables. Chen et al. (2000) presented a model for mass flow in adiabatic capillary tubes based on the two-phase viscosity model published by McAdams et al. (1942). The predicted flow rates of this model were within 5% of the predicted mass flow rates from Kuehl and Goldschmidt (1990).

A dimensionless general prediction correlation was developed by Choi et al. (2003) based on test data of R-22, R-407C, and R-290 with the average and standard deviations being 0.9% and 5.0%, respectively. The verification of the correlation with test data of previous researchers showed that the average and standard deviations were 0.73% and 6.16%, respectively.

Choi et al. (2004) also presented a study of adiabatic capillary tube. In this study, a general correlation for R12, R22, R134a, R152a, R407C, and R410A was formulated. The data sources to develop this correlation included Wolf et al. (1995), Melo et al. (1999), Kim et al. (1999), Hong et al. (2000), and Fiorelli et al. (2002). This correlation reflected a mean deviation of 5.4%, a standard deviation of 6.5% and an average deviation of 0.7%. Rating charts to predict the mass flow in adiabatic capillary tubes were also developed for the six refrigerants.

Yang and Wang (2008) presented an empirical general correlation to predict the mass flow through adiabatic capillary tubes. Eight refrigerants (R12, R22, R134a, R290, R407c, and R404a) were included in this study. The measured data from these refrigerants were from ten previous researchers. The dimensionless parameters used in this study were quite different from previous researchers with the average deviation being -0.83% and the standard deviation being 9.02%

Sarker and Jeong (2012) developed an empirical correlation for heat exchangers. In their study, the data used to create the correlation was taken from a numerical mechanistic model rather than experimental data. The model agreed with the experimental data from the open literature.

Shao et al. (2013) reviewed the dimensionless prediction correlations for the refrigerant mass flows in adiabatic capillary tubes. The correlations were categorized by the dimensionless parameters and experimental data from other research studies was used for the validation. The conclusion showed that the correlation performance varied in accuracy for different refrigerant mass flows in the adiabatic capillary tubes.

CHAPTER III

METHODOLOGY DESCRIPTION

The methodology to be used in this thesis is a regression of non-dimensional parameters generated from the Buckingham Pi Theorem. The geometric factors and fluid properties that affect refrigerant flow rate through adiabatic capillary tubes and capillary tube/suction line heat exchangers are used to define non-dimensional mass flow rate parameters according to the Buckingham Pi Theorem (Buckingham, 1914). The results are correlated with experimental data to create dimensionless Pi-term equations that can then be used to predict mass flow rates.

3.1. Prediction Methods for Adiabatic Capillary Tube

The method to predict the refrigerant mass flow in adiabatic capillary tubes used in Chapters 5, 7, and 8 is a multiple regression of dimensionless parameters applying the Buckingham Pi theorem. This method is described in this section.

3.1.1. Definition of Non-Dimensional Parameters

The geometric factors that are significant to the adiabatic capillary tube flow rate include capillary tube length, diameter, and refrigerant inlet conditions and pressures, while the applicable fluid properties include specific volume, viscosity, surface tension, specific heat and enthalpy of formation. As shown in Equation 3.1, the flow rate can be determined as a function of these design variables and fluid properties.

$$\dot{m} = f1(Lc, Dc, h, \nu, \mu, \sigma, Cp, Pcapin, \Delta Tsc) \tag{3.1}$$

Using the Buckingham Pi Theorem, the result is the eight dimensionless parameters outlined in Table 3.1. Furthermore, table 3.2 presents the factors that each parameter includes.

Table 3.1 Summary of Dimensionless Parameters for Adiabatic Capillary Tube

Pi-parameter	Definition	Description
π_1	L_c / D_c	Geometry Effect
π_2	$(h_{fgc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$	Vaporization Effect
π_3	$D_c\, \sigma / \nu_{fc}^2\, \mu_{fc}^2$	Bubble Formation
π_4	$(P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$	Inlet Pressure
π_5 (subcooled)	$(\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$	Inlet Condition
π_5 (quality)	x	Inlet Condition
π_6	ν_{gc} / ν_{fc}	Density Effect
π_7	$(\mu_{fc} - \mu_{gc})/\mu_{fc}$	Viscous Effect
π_8	$\dot{m}/(D_c \,.\, \mu_{fc})$	Flow Rate

Table 3.2 Parameters Check list for Adiabatic Capillary Tube

	Geometries		Fluid Characters				Fluid Properties						
	Lc	Dc	$\dot{m}$	Pcapin	ΔTsc	X	h_{fg}	ν_f	ν_g	μ_f	μ_g	σ	Cp_f
π_1	√	√											
π_2		√					√	√		√			
π_3		√						√		√		√	
π_4		√		√				√		√			
π_5(Subcooled)		√			√			√		√			√
π_5(Quality)						√							
π_6								√	√				
π_7										√	√		
π_8		√	√							√			

3.1.2. Summary of Dimensionless Terms

A brief description of the importance of each dimensionless parameter is discussed below.

π_1 (Geometry Effect)

The mass flow rate would be expected to increase with increasing diameter because of the flow area increasing and then decrease with increasing length because of the extra frictional resistance of the increased length.

π_2 (Vaporization Effect)

The enthalpy would be expected to affect the potential of the refrigerant vaporization.

π_3 (Bubble Formation)

The surface tension is a crucial element to form bubbles in the flashing of refrigerant through the capillary tube.

π_4 (Inlet Pressure)

The mass flow rate would be expected to rise with the increase of the upstream pressure as the additional pressure could force more refrigerant to enter the capillary tube.

π_5 (Inlet Condition)

The mass flow rate increases with inlet subcooling because it results in a longer liquid region in the capillary tube and a lesser amount of quality, with both affects resulting in a lesser restriction to the flow.

π_6 (Density Effect)

The refrigerant specific volume would be expected to have an effect on mass flow rate, which is directly proportional to refrigerant density.

π_7 (Viscous Effect)

The mass flow rate increases with decreasing fluid viscosity, which mean less resistance to the flow.

π_8 (Flow Rate)

This term is the dependent variable of the correlation.

3.1.3. Equation Development

A regression of π8, the flow rate term, is developed into a functional relationship of the other dimensionless terms, as shown in Equation 3.2:

$$\pi_8 = f2(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7)$$
$$\pi_8 = \text{constant} * \pi_1^{A} * \pi_2^{B} * \ldots\ldots * \pi_7^{G} \quad (3.2)$$

By taking the log of each side of Equation 3.2 as shown in Equation 3.3, it is then possible to perform a linear regression to determine the coefficients for each pi-parameter.

$$\text{Log}(\pi_8) = A * \text{Log}(\pi_1) + B * \text{Log}(\pi_2) + \ldots\ldots\ldots G * \text{Log}(\pi_7) + \text{intercept} \quad (3.3)$$

The final form of the prediction equation then is determined by raising 10 to each side of Equation 3.3 and recombining the terms as shown in Equation 3.4

$$\pi_8 = 10\text{intercept} * \pi_1^{A} * \pi_2^{B} * \ldots\ldots * \pi_7^{G} \quad (3.4)$$

The resulting prediction equation then is functions of these dimensionless numbers raised to empirically determined powers. The linear regression then is performed using the experimental data to determine the coefficients through (A …G) and the intercept in equation 3.4. A criterion of 95% significance in conjunction with R2 values is used to determine those Pi terms that remain in the final prediction equations (R. R. Bittle et.al 1998).

3.2. Prediction Methods for Capillary Tube/Suction Line Heat Exchangers

The method used to predict the refrigerant mass flow in adiabatic capillary tubes in this study is a multiple regression of dimensionless parameters based on the Buckingham Pi theorem.

3.2.1. Definition of Non-dimensional Parameters

The following factors are significant to the heat exchanger flow rate: capillary tube inlet pressure, suction line inlet pressure, capillary tube inlet temperature, superheat temperature at suction line inlet, capillary tube inside diameter, suction line inside diameter, capillary tube length, heat exchange length, and adiabatic entrance length. All of these factors are necessary for refrigerant flow rate predictions. Relevant fluid properties of the refrigerant in the capillary tube and suction line are also required for refrigerant flow rate predictions, properties such as viscosity, specific volume, specific heat and enthalpy

The result is that the heat exchanger refrigerant flow rate is a function of design variables and fluid properties shown in Equation 3.5

$$\dot{m} = f1(Lc, Dc, Li, Lhx, Ds, h, \nu, \mu, Cp, Pcapin, Psuctin, \Delta Tsc, \Delta Tsh) \qquad (3.5)$$

Applying the Buckingham Pi Theorem results in the fifteen dimensionless quantities, called Pi terms, shown in Table 3.3 in one or more Pi terms, while Table 3.4 shows how each parameter is included.

Table 3.3 Summary of Dimensionless Parameters for Heat Exchangers

Pi-parameter	Definition	Description
π_1	L_c / D_c	Geometry Effect
π_2	L_i / D_c	Geometry Effect
π_3	L_{hx}/ D_c	Geometry Effect
π_4	D_s / D_c	Geometry Effect
π_5	$(P_{capin} . D_c^2)/(\mu_{fc}^2 . \nu_{fc})$	Capillary Inlet Pressure
π_6	$(P_{suctin} . D_c^2)/(\mu_{fc}^2 . \nu_{fc})$	Suction Inlet Pressure
π_7 (subcooled)	$(\Delta T_{sc} . C_{pfc} . D_c^2)/(\mu_{fc}^2 . \nu_{fc}^2)$	Capillary Inlet Condition
π_7 (quality)	x	Capillary Inlet Condition
π_8	$(\Delta T_{sh} . C_{pfc} . D_c^2)/(\mu_{fc}^2 . \nu_{fc}^2)$	Suction Inlet Condition
π_9	$\dot{m} /(D_c . \mu_{fc})$	Flow Rate
π_{10}	ν_{gc} / ν_{fc}	Density Effect
π_{11}	$(\mu_{fc}- \mu_{gc})/ \mu_{fc}$	Viscous Effect
π_{12}	$(h_{fgc} . D_c^2)/(\mu_{fc}^2 . \nu_{fc}^2)$	Vaporization Effect
π_{13}	μ_{gc}/ μ_{fc}	Viscous Effect
π_{14}	ν_{gc}/ ν_{fc}	Density Effect
π_{15}	C_{pgc}/ C_{pfc}	Specific Heat Effect

Table 3.4 Parameters Check List for Heat Exchangers

		π_1	π_2	π_3	π_4	π_5	π_6	π_7 (Subcooled)	π_7 (Quality)	π_8	π_9	π_{10}	π_{11}		π_{12}	π_{13}	π_{14}	π_{15}
Geometries	Lc	√																
	Li		√															
	Lhx			√														
	Dc	√	√	√	√	√	√	√		√	√				√			
	Ds				√													
Fluid Characters	$\dot{m}$										√							
	Pcapin					√												
	Psucin						√											
	ΔTsc							√										
	ΔTsh									√								
	X								√									
Fluid Properties	h_{fgc}														√			
	ν_{fc}					√	√	√		√		√			√		√	
	ν_{gc}											√						
	ν_{gs}																√	
	μ_{fc}					√	√	√		√	√		√		√	√		
	μ_{gc}												√					
	μ_{gs}															√		
	Cp_{fc}							√		√								√
	Cp_{gc}																	√

3.2.2. Summary of Dimensionless Terms

A brief description of the importance of each dimensionless parameter is discussed below.

π_1 (Geometry Effect)

The mass flow rate would be expected to rise with the diameter increasing because of the flow area increasing and decrease with the length increasing because of the extra frictional resistance of the increased length.

π_2 (Geometry Effect)

The increase in the adiabatic entrance length would be expected to increase the mass flow rate when the two-phase flow occurs at the upstream of the capillary tube.

π_3 (Geometry Effect)

The increase in the heat exchange length would be expected to increase the mass flow rate. The two-phase acceleration would be decreased because more thermal energy would be transferred from the capillary tube to the suction line.

π_4 (Geometry Effect)

The Reynolds number is affected by the increase in the suction line diameter.

π_5 (Capillary Inlet Pressure)

The mass flow rate would be expected to rise with the increase of the upstream pressure, as more refrigerant could be forced to enter the capillary tube by the additional pressure.

π_6 (Suction Inlet Pressure)

The pressure increase in the suction line would be expected to decrease the mass flow rate, because the suction line inlet temperature would increase with the pressure increase in the suction line at a fixed super heat condition, as a result the heat transfer would decrease.

π_7 (Capillary Inlet Condition)

The mass flow rate increases with inlet subcooling because it results in a longer liquid region in the capillary tube, and a lesser amount of quality, with both affects resulting in a lesser restriction to the flow.

π_8 (Suction Inlet Condition)

The increasing superheat level at the suction line inlet would decrease the mass flow rate, this increase could increase the temperature at the suction line inlet, which decrease, the heat transfer.

π_9 (Flow Rate)

This term is the dependent variable of the correlation.

π_{10} (Density Effect)

The refrigerant specific volume would be expected to have an effect on mass flow rate which is directly proportional to refrigerant density.

π_{11} (Viscous Effect)

The mass flow rate increases with decreasing fluid viscosity, which causes less resistance to the flow.

π_{12} (Vaporization Effect)

The enthalpy would be expected to affect the potential of the refrigerant vaporization.

π_{13} (Viscous Effect)

The mass flow rate increases with decreasing fluid viscosity, which mean less resistance to the flow.

π_{14} (Density Effect)

The refrigerant specific volume would be expected to have an effect on mass flow rate which is directly proportional to refrigerant density.

π_{15} (Specific Heat Effect)

This parameter was also included, but was not considered to have significant effect.

3.2.3. Equation Development

A regression of π_9 which is the flow rate term is developed as a function of the other dimensionless terms. A form of this relationship is shown in Equation 3.6:

$$\pi_9=f2(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}, \pi_{11}, \pi_{12}, \pi_{13}, \pi_{14}, \pi_{15}) \qquad (3.6)$$

The same procedure that was used for the adiabatic capillary tube and explained in the previous section is used here for the heat exchanger.

CHAPTER IV.

DATABASE DESCRIPTION

As described in Chapter 3, the refrigerant mass flow rate in capillary tubes is governed by tube geometries, condition effects, and fluid properties. The database of tube geometries and fluid characteristics are taken from previous ASHRAE research studies. Two kinds of expansion devices: adiabatic capillary tubes and capillary tube/suction line heat exchangers are simulated in this study, which require two kinds of databases. The fluid property data is taken from the National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties, Standard Reference Database 23, Version 9.1 (NIST 2013).

4.1. Experimental Database

The experimental fluid characteristics data along with the geometric factor data needed to develop models for adiabatic capillary tubes can be found in “Adiabatic Capillary Tube Performance with Alternative Refrigerants” RP-762 ASHRAE Final Report 1995 by D A. Wolf, R. R. Bittle and M. B. Pate. Four refrigerants: R-134a, R-22, R-410A, and R-152a were included in the adiabatic capillary tube study. These refrigerants represent a typical range of refrigerant properties in capillary tube systems. It is important to include a variation in refrigerant properties, because refrigerant properties are used to develop the prediction correlations. Also the capillary tube geometry database is varied over a wide range, while the capillary tube diameters ranged from 0.026 in. (0.66 mm) to 0.100 in. (2.54 mm). The capillary tube lengths ranged from

20in. (508 mm) to 200 in. (5080 mm). The databases represent a wide range of inlet conditions of capillary tubes, with the he condenser temperatures ranging from 60 ℉ to 120 ℉ (15.6℃ to 48.9℃).

In the case of capillary tube/suction line heat exchangers, the experimental data was taken from “Capillary Tube/suction Line Heat Exchangers Performance with Alternative Refrigerants” 948-RP ASHRAE Final Report 2002 by D. A. Wolf and M. B. Pate. Five refrigerants: R-134a, R-22, R-410A, R-610a and R-152a were included in the capillary tube/suction line heat exchanger study. These refrigerants cover a typical range of refrigerant properties in capillary tube systems. because refrigerant properties are used to develop the prediction correlations, it is important to include a variation in refrigerant properties. For the capillary tube/suction line heat exchanger study, the capillary tube diameters ranged from 0.026 in. (0.66 mm) to 0.042 in. (1.05 mm), the lengths ranged from 80 in. (2032 mm) to 180 in. (4572 mm). While heat exchanger lengths varied from 20 in. (508 mm) to 100 in. (2540 mm). Adiabatic entrance lengths ranged from 6 in. (152.4 mm) to 24 in. (609.6 mm), while the suction line diameters ranged from 0.194 in. (4.9276 mm) to 0.319 in. (8.1026 mm). The databases also represent a wide range of capillary tube inlet conditions. For example the condenser temperatures varied from 60 ℉ to 120 ℉ (15.6℃ to 48.9℃).

4.2. Fluid Property Database

The fluid properties of all refrigerants used for the present study were taken from the National Institute of Standards and Technology Reference Fluid Thermodynamic and Transport Properties, Standard Reference Database 23, Version 9.1 (NIST 2013). However, the fluid properties from NIST 1991 were applied in "Adiabatic Capillary Tube Performance with Alternative Refrigerants" RP-762 ASHRAE Final Report 1995, and the fluid properties from NIST 1996 were applied in "Capillary Tube/Suction Line Heat Exchangers Performance with Alternative Refrigerants" 948-RP ASHRAE Final Report 2002. Therefore, a fluid property comparison of NIST 1991, NIST 1996 and NIST 2013 is necessary. The comparisons for R-134a, R-22, R-410a, and R-600a are listed in Table 4. 1 at a temperature of 100 ℉.

The percent difference of the properties among the three data sources are listed in Table 4.2 with Equation 4.1 being used to calculate the difference.

$$\%difference = \frac{(NISTnew\ property - NISTold\ property)*100}{NISTold\ \ Proterty}\ \% \qquad (4.1)$$

The viscosity of R-410a changed the most, 39.05%, while enthalpy of R600a changed the least, only 0.01%. The fluid property changes of R-134a, R-22, R-410a, R-152a, and R-600a may impact mass flow changes to different degrees.

Table 4.1 Fluid Property Comparison for NIST 1991, NIST 1996, and NIST 2013

R-134a						
Property Data Source	vf (ft3/lbm)	vg (ft3/lbm)	µf (lbm/ft h)	µg (lbm/ft h)	h fg (Btu/lbm)	**Cp** f (Btu/lbm °F)
NIST 1991	0.01390	0.3408	0.442	0.031	71.20	0.357
NIST 1996	0.01386	0.3411	0.441	0.031	71.23	0.356
NIST 2013	0.01386	0.3407	0.402	0.030	71.13	0.355
R-22						
Property Data Source	vf (ft3/lbm)	vg (ft3/lbm)	µf (lbm/ft h)	µg (lbm/ft h)	h fg (Btu/lbm)	**Cp** f (Btu/lbm °F)
NIST 1991	0.0142	0.2562	0.405	0.0340	71.20	0.330
NIST 1996	0.0141	0.2527	0.363	0.0339	71.68	0.325
NIST 2013	0.0141	0.2566	0.344	0.0320	72.77	0.317
R-410a						
Property Data Source	vf (ft3/lbm)	vg (ft3/lbm)	µf (lbm/ft h)	µg (lbm/ft h)	h fg (Btu/lbm)	**Cp** f (Btu/lbm °F)
NIST 1991	0.0158	0.1797	0.393	0.0360	74.80	0.408
NIST 1996	0.0161	0.1717	0.2488	0.0358	73.38	0.451
NIST 2013	0.0162	0.1685	0.2396	0.0355	71.91	0.452
R-600a						
Property Data Source	vf (ft3/lbm)	vg (ft3/lbm)	µf (lbm/ft h)	µg (lbm/ft h)	h fg (Btu/lbm)	**Cp** f (Btu/lbm °F)
NIST 1991	0.03	1.241	0.350	0.020	135.16	0.627
NIST 1996	0.03	1.245	0.314	0.0195	135.43	0.609
NIST 2013	0.03	1.242	0.320	0.0190	135.18	0.602
R-152a						
Property Data Source	vf (ft3/lbm)	vg (ft3/lbm)	µf (lbm/ft h)	µg (lbm/ft h)	h fg (Btu/lbm)	**Cp** f (Btu/lbm °F)
NIST 1991	0.0185	0.6084	0.309	0.036	116.6	0.456
NIST 1996	0.0185	0.6023	0.3422	0.0265	113.14	0.447
NIST 2013	0.0185	0.6023	0.3404	0.0256	113.14	0.447

Table 4.2 Fluid Property Difference for NIST 1991, NIST 1996, and NIST 2013

R-134a						
Property Data Source	vf	vg	µf	µg	h fg	**Cp** f
NIST 1991 VERSUS NIST 1996	-0.29%	0.09%	-0.23%	1.10%	0.04%	-0.42%
NIST 1996 VERSUS NIST 2013	-0.03%	-0.12%	-8.90%	-5.34%	-0.14%	-0.11%
NIST 1991 VERSUS NIST 2013	-0.32%	-0.03%	-9.11%	-4.30%	-0.10%	-0.53%
R-22						
Property Data Source	vf	vg	µf	µg	h fg	**Cp** f
NIST 1991 VERSUS NIST 1996	-0.92%	-1.37%	-10.37%	-0.26%	0.67%	-1.42%
NIST 1996 VERSUS NIST 2013	0.02%	1.55%	-5.17%	-5.69%	1.52%	-2.69%
NIST 1991 VERSUS NIST 2013	-0.89%	0.16%	-15.00%	-5.94%	2.21%	-4.07%
R-410a						
Property Data Source	vf	vg	µf	µg	h fg	**Cp** f
NIST 1991 VERSUS NIST 1996	1.65%	-4.45%	-36.69%	-0.56%	-1.90%	10.51%
NIST 1996 VERSUS NIST 2013	0.87%	-1.88%	-3.72%	-0.86%	-2.00%	0.35%
NIST 1991 VERSUS NIST 2013	2.53%	-6.25%	-39.05%	-1.41%	-3.86%	10.90%
R-600a						
Property Data Source	vf	vg	µf	µg	h fg	**Cp** f
NIST 1991 VERSUS NIST 1996	-0.03%	0.33%	-10.43%	-2.40%	0.20%	-2.90%
NIST 1996 VERSUS NIST 2013	-0.01%	-0.25%	2.14%	-2.74%	-0.18%	-1.13%
NIST 1991 VERSUS NIST 2013	-0.04%	0.08%	-8.51%	-5.07%	0.01%	-4.00%
R-152a						
Property Data Source	vf	vg	µf	µg	h fg	**Cp** f
NIST 1991 VERSUS NIST 1996	0.00%	-1.00%	10.74%	-26.53%	-2.97%	-1.95%
NIST 1996 VERSUS NIST 2013	0.01%	0.00%	-0.52%	-3.31%	0.00%	0.00%
NIST 1991 VERSUS NIST 2013	0.01%	-1.01%	10.17%	-28.96%	-2.97%	-1.95%

CHAPTER V

REFRIGERANT SPECIFIC CORRELATIONS FOR ADIABATIC CAPILLARY TUBES

This chapter presents the mass flow predictions for each pure refrigerant (R-134a, R-22, and R-410A) in adiabatic capillary tubes. Correlations for both subcooled inlet conditions and quality inlet conditions are developed for each refrigerant. These correlations are regressions of non-dimensional parameters including geometry factors, condition effects, and fluid properties based on the Buckingham Pi Theorem. A more detailed discussion of this method was described previously in Chapter 3.

5.1. R-134a Correlations for Adiabatic Capillary Tubes

This section describes the correlation to predict the pure R-134a mass flow rate in adiabatic capillary tubes, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation.

5.1.1. Correlation for Subcooled Inlet Conditions

This correlation was formulated from the database for R-134a with subcooled inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.1.

Table 5.1 Adiabatic Capillary Tubes Subcooled Inlet Conditions for R-134a

Operating Variable	Data range
ΔT_{sh}	10 to 31 ℉
Pcapin	124.9 to 199.59 psia

The final correlation to predict the mass flow of R-134a through adiabatic capillary tubes with subcooled conditions is shown in Equation 5.1.

$$\pi_8 = 0.0176 * \pi_1^{-0.5194} * \pi_3^{-1.567} * \pi_4^{1.354} * \pi_7^{1.629} \qquad (5.1)$$

where $\pi_8 = \dot{m}/(D_c \cdot \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_3 = D_c \, \sigma / \nu_{fc}^2 \, \mu_{fc}^2$

$\pi_4 = (P_{capin} \cdot D_c^2)/(\mu_{fc}^2 \cdot \nu_{fc})$

$\pi_7 = (\mu_{fc} - \mu_{gc})/\mu_{fc}$

The measured mass flows are compared to the predicted mass flows in Figure 5.1. The deviations ranged from 0.29% to 3.50% (Figure 5.2), while the average deviation was 1.65%. The R^2 of the correlation was 0.996.

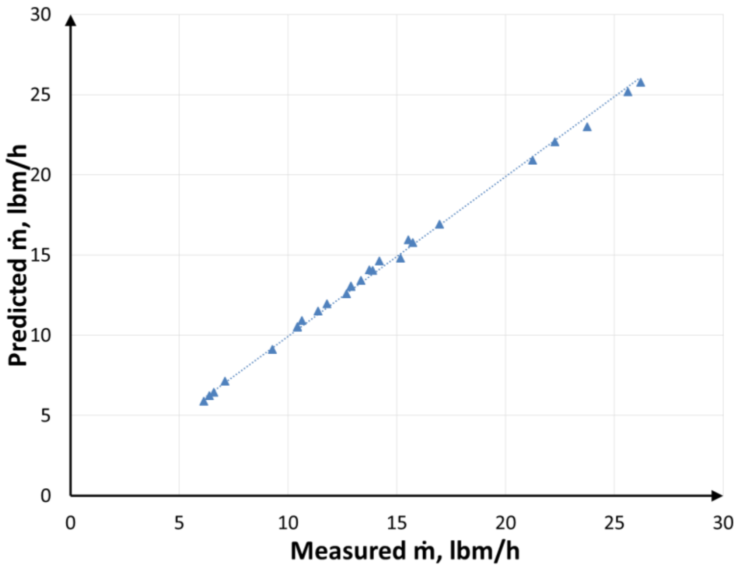

Figure 5.1 R-134a: Measured Mass Flow versus Predicted Mass Flow for Adiabatic Capillary Tubes with Subcooled InletConditions

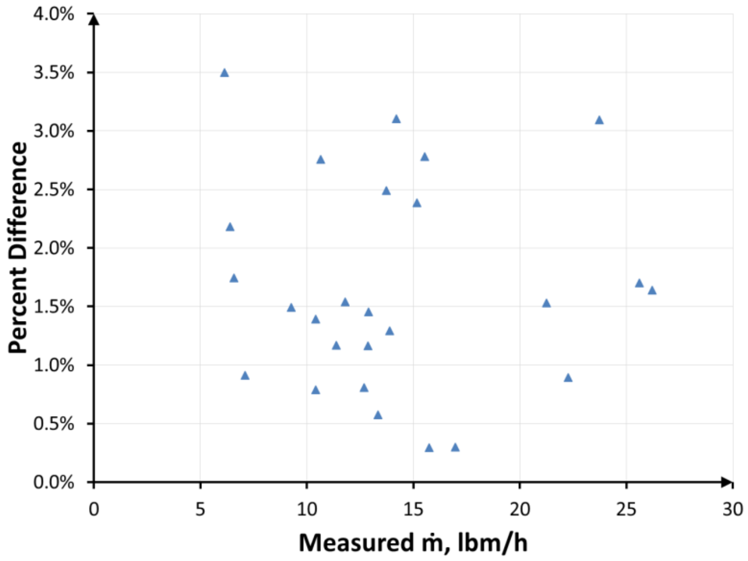

Figure 5.2 R-134a: Deviation Distribution for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

5.1.2. Correlation for Quality Inlet Conditions

This correlation was formulated from the database for R-134a with quality inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.2

Table 5.2 Adiabatic Capillary Tubes Quality Inlet Conditions for R-134a

Operating Variable	Data range
Quality	0.055 to 0.605
Pcapin	124.9 to 174.99 psia

The final correlation to predict the mass flow of R-134a through adiabatic capillary tubes with quality conditions is shown in Equation 5.2.

$$\pi_8 = 0.00594 * \pi_1^{-0.362} * \pi_4^{1.663} * \pi_5^{-0.308} \tag{5.2}$$

where $\pi_8 = \dot{m}/(D_c \cdot \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_4 = (P_{capin} \cdot D_c^2)/(\mu_{fc}^2 \cdot \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \cdot C_{pfc} \cdot D_c^2)/(\mu_{fc}^2 \cdot \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 5.3. The deviations ranged from 0.44% to 13.50% (Figure 5.4), while the average deviation was 6.30%. The R^2 of the correlation was 0.955.

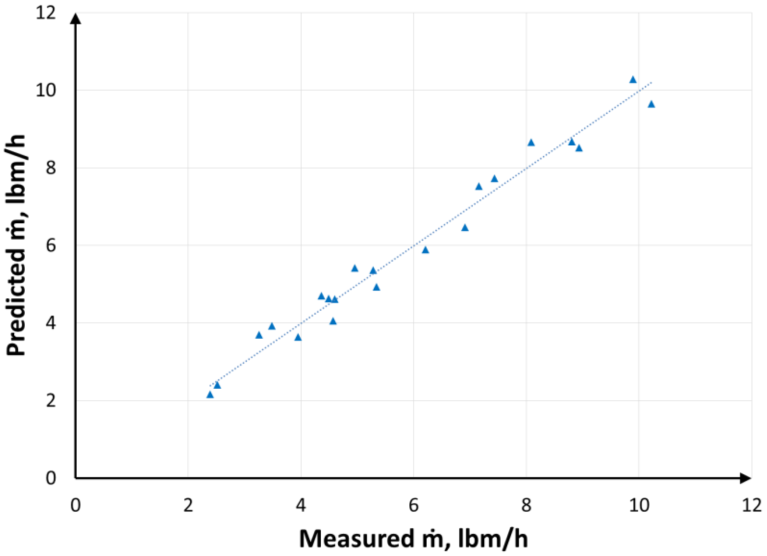

Figure 5.3 R-134a: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

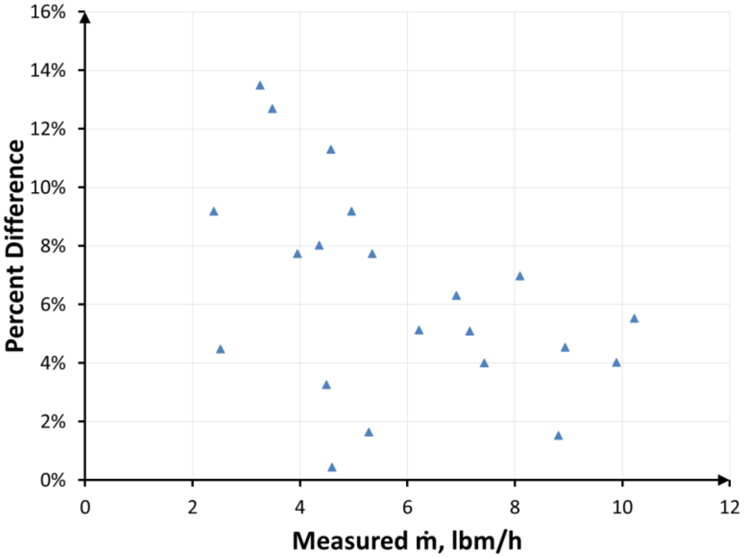

Figure 5.4 R-134a: Deviation Distributions for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

5.2. R-22 Correlations for Adiabatic Capillary Tubes

This section describes the correlation to predict the pure R-22 mass flow rate in adiabatic capillary tubes, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation.

5.2.1. Correlation for Subcooled Inlet Conditions

This correlation was formulated from the database for R-22 with subcooled inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.3

Table 5.3 Adiabatic Capillary Tubes Subcooled Inlet Conditions for R-22.

Operating Variable	Data range
ΔT_{sh}	2 to 30 ℉
Pcapin	209.6 to 399.58 psia

The final correlation to predict the mass flow of R-22 through adiabatic capillary tube with subcooled conditions is shown in Equation 5.3.

$$\pi_8=0.4360*\pi_1^{-0.449}*\pi_4^{0.396}*\pi_5^{0.166} \tag{5.3}$$

where $\pi_8 = \dot{m}/(D_c \, . \, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_4 = (P_{capin} \, . \, D_c^2)/(\mu_{fc}^2 \, . \, \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 5.5. The deviations ranged from 0.01% to 6.16% (Figure 5.6), while the average deviation was 2.51%. The R^2 of the correlation was 0.993.

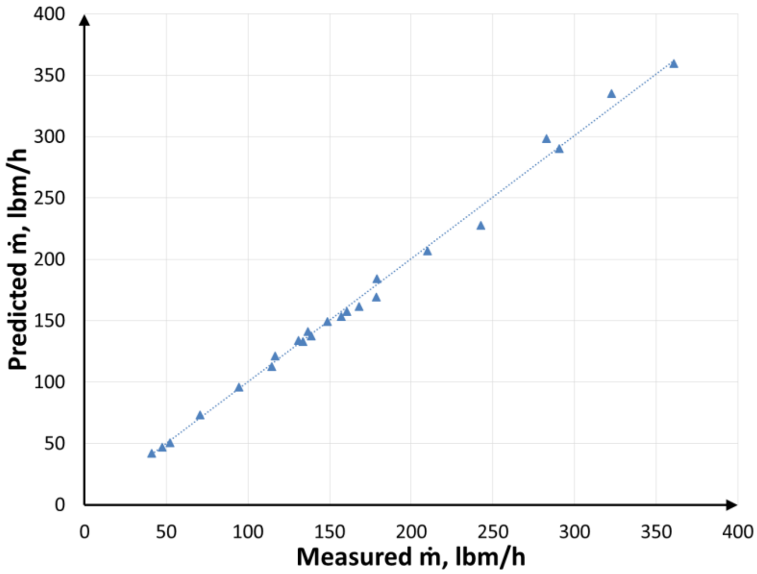

Figure 5.5 R-22: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcooled Inlet Conditions.

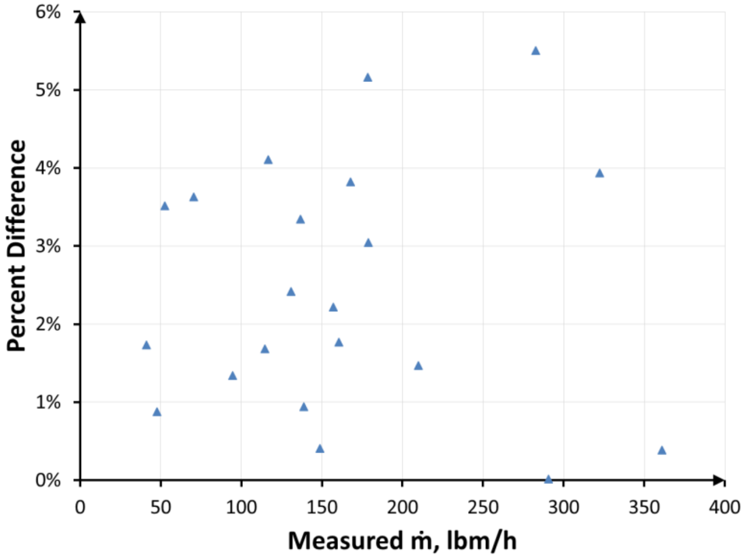

Figure 5.6 R-22: Deviation Distributions for Adiabatic Capillary Tubes with Subcooled Inlet Conditions.

5.2.2. Correlation for Quality Inlet Conditions

This correlation was formulated from the database for R-22 with quality inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.4

Table 5.4 Adiabatic Capillary Tubes Quality Inlet Conditions for R-22.

Operating Variable	Data range
Quality	0.003 to 0.085
Pcapin	210.15 to 271.12 psia

The final correlation to predict the mass flow of R-22 through adiabatic capillary tube with quality conditions is shown in Equation 5.4.

$$\pi_8 = 0.06899 * \pi_1^{-0.353} * \pi_4^{0.600} * \pi_5^{-0.0468} \tag{5.4}$$

where $\pi_8 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_4 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 5.7. The deviations ranged from 0.10% to 8.88% (Figure 5.8), while the average deviation was 3.82%. The R2 of the correlation was 0.985.

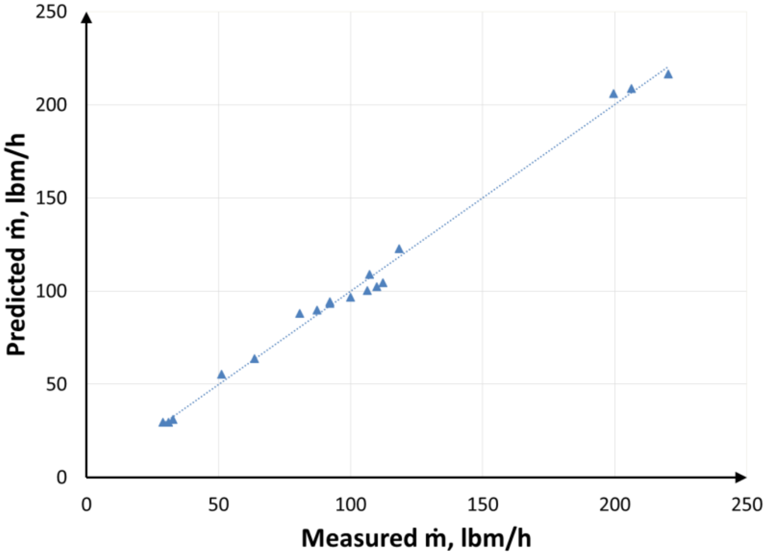

Figure 5.7 R-22: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Quality Inlet Conditions.

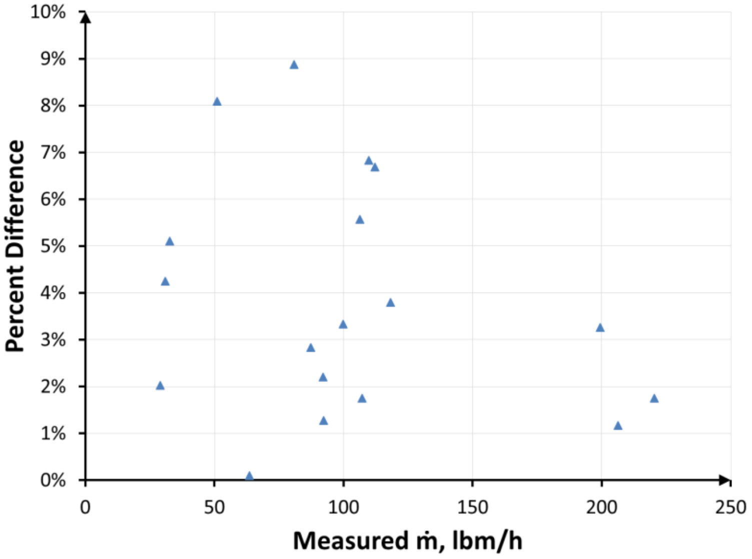

Figure 5.8 R-22: Deviation Distributions for Adiabatic Capillary Tubes with Quality Inlet Conditions.

5.3. R-410a Correlation for Adiabatic Capillary Tubes

This section describes the correlation to predict the pure R-410a mass flow rate in adiabatic capillary tubes, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation.

5.3.1. Correlation for Subcooled Inlet Conditions

This correlation was formulated from the database for R-410a with subcooled inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.5

Table 5.5 Adiabatic Capillary Tubes Subcooled Inlet Conditions for R-410a.

Operating Variable	Data range
ΔT_{sh}	10 to 34 ℉
Pcapin	330 to 390.9 psia

The final correlation to predict the mass flow of R-410a through adiabatic capillary tubes with subcooled conditions is shown in Equation 5.5.

$$\pi_8 = 0.2809 * \pi_1^{-0.513} * \pi_4^{0.405} * \pi_5^{0.192} \qquad (5.5)$$

where $\pi_8 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_4 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 5.9. The deviations ranged from 0.15% to 3.27% (Figure 5.10) while the average deviation was 1.75%. The R^2 of the correlation was 0.995.

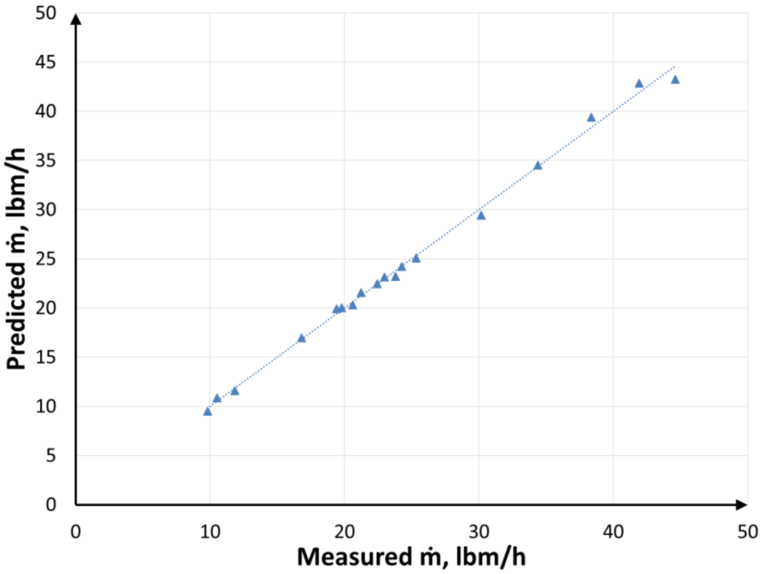

Figure 5.9 R-410a: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcooled Inlet Conditions.

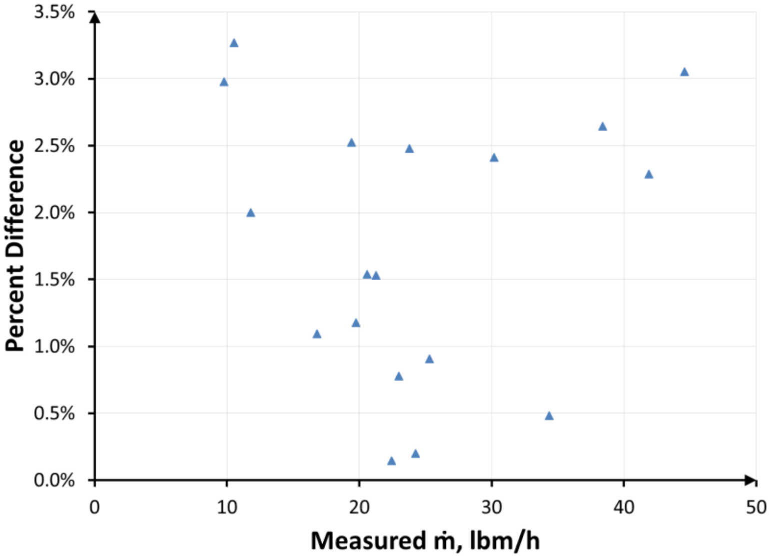

Figure 5.10 R-410a: Deviation Distributions for Adiabatic Capillary Tubes with Subcooled Inlet Conditions.

5.3.2. Correlation for Quality Inlet Conditions

This correlation was formulated from the database for R-410a with quality inlet conditions in adiabatic capillary tubes. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 5.6

Table 5.6 Adiabatic Capillary Tubes Quality Inlet Conditions for R-410a.

Operating Variable	Data range
Quality	0.038 to 0.36
Pcapin	327 to 393.2 psia

The final correlation to predict the mass flow of R-410a through adiabatic capillary tubes with quality conditions is shown in Equation 5.6.

$$\pi_8 = 0.1288 * \pi_1^{-0.6513} * \pi_4^{0.7863} * \pi_5^{-0.1365} \tag{5.6}$$

where $\pi_8 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_4 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 5.11. The deviations ranged from 0.86% to 12.87% (Figure 5.12) while the average deviation was 4.61%. The R^2 of the correlation was 0.976.

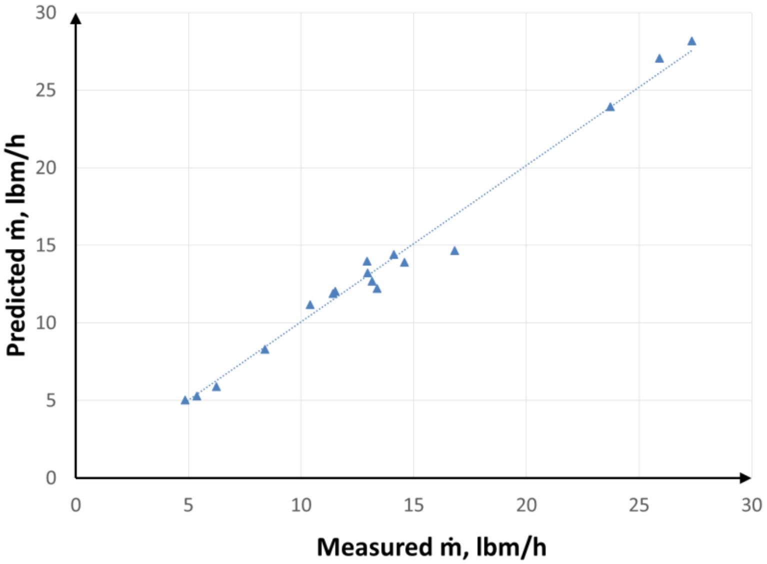

Figure 5.11 R-410a: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Quality Inlet Conditions.

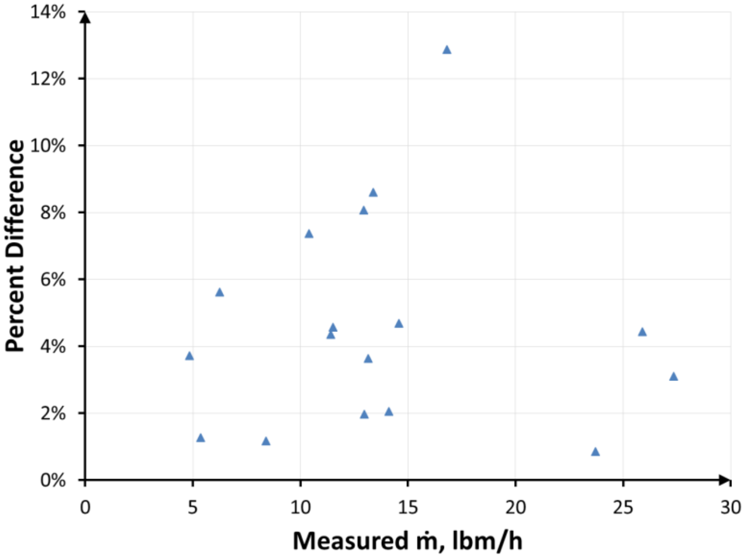

Figure 5.12 R-410a: Deviation Distributions for Adiabatic Capillary Tubes with Quality Inlet Conditions.

CHAPTER VI

SPECIFIC REFRIGERANT CORRELATIONS FOR HEAT EXCHANGERS

This chapter describes the mass flow predictions for each pure refrigerant (R-134a, R-22, R-410A, and R600a) in capillary tubes/suction line heat exchangers. Correlations for subcooled inlet conditions are developed for each refrigerant based on regressions of non-dimensional parameters including geometry factors, fluid condition effects, and fluid properties by using the Buckingham Pi Theorem. A more detailed discussion of the method was presented in Chapter 3.

6.1. R-134a Correlation for Heat Exchangers

This section describes the correlation to predict the pure R-134a mass flow rate in capillary tubes/suction line heat exchangers, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation. This correlation was formulated from the database for R-134a with subcooled inlet conditions in capillary tube/suction line heat exchangers. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 6.1

Table 6.1 Heat Exchangers Subcooled Inlet Conditions for R-134a.

Operating Variable	Data range
Pcapin	100 to 200 psia
ΔT_{sc}	5to 30℉
Psuction	16 to 32 psia
ΔT_{sh}	3 to 35℉

The final correlation to predict the mass flow of R-134a through capillary tube heat exchangers with subcooled conditions is shown in Equation 6.1.

$$\pi_9=0.6688 * \pi_1^{-0.6081} * \pi_3^{0.08049} * \pi_5^{0.6482} * \pi_6^{-0.1125} * \pi_7^{-0.04968} \tag{6.1}$$

where $\pi_9 = \dot{m}/(D_c . \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_3 = L_{hx}/ D_c$

$\pi_5 = (P_{capin} . D_c^2)/(\mu_{fc}^2 . \nu_{fc})$

$\pi_6 = (P_{suctin} . D_c^2)/(\mu_{fc}^2 . \nu_{fc})$

$\pi_7 = (\Delta T_{sc} . C_{pfc} . D_c^2)/(\mu_{fc}^2 . \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 6.1. The deviations ranged from 0.10% to 6.51% (Figure 6.2), while the average deviation was 2.29%. The R^2 of the correlation was 0.986.

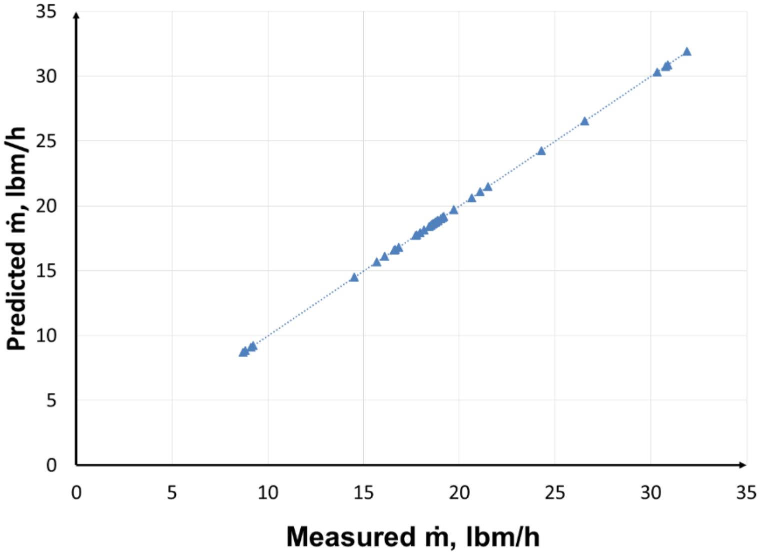

Figure 6.1 R-134a: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

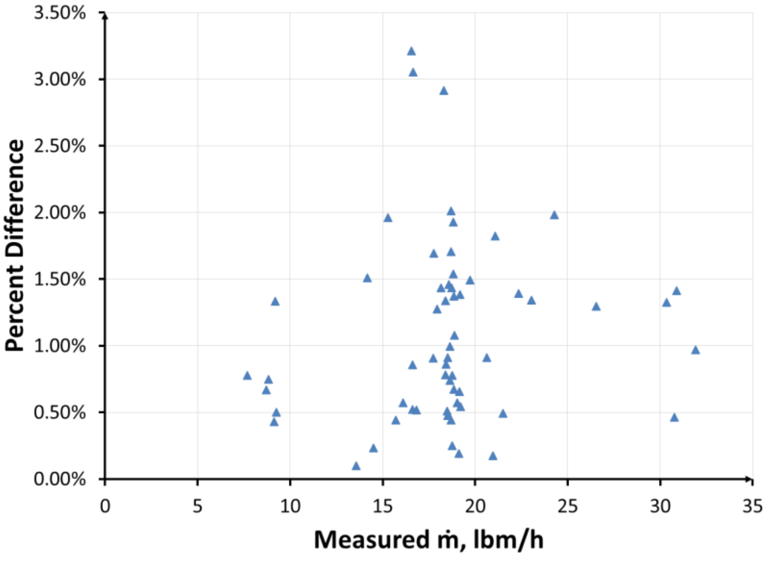

Figure 6.2 R-134a: Deviation Distributions for Heat Exchangers with Subcooled Inlet Conditions

6.2. R-22a Correlation for Heat Exchangers

This section describes the correlation to predict the pure R-22 mass flow rate in capillary tubes/suction line heat exchangers, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation. This correlation was formulated from the database for R-22 with subcooled inlet conditions in capillary tube/suction line heat exchangers. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 6.2

Table 6.2 Heat Exchangers Subcooled Inlet Conditions for R-22.

Operating Variable	Data range
Pcapin	180 to 300 psia
ΔT_{sc}	10 to 30 ℉
Psuction	40 to 80 psia
ΔT_{sh}	3 to 45 ℉

The final correlation to predict the mass flow of R-22 through capillary tube heat exchangers with subcooled conditions is shown in Equation 6.2.

$$\pi_9=0.000182 * \pi_1^{-0.4750} * \pi_3^{0.1896} * \pi_5^{0.4544} * \pi_7^{-0.1620} * \pi_{10}^{-2.7435} * \pi_{13}^{-5.548} \quad (6.2)$$

where $\pi_9 = \dot{m}/(D_c \, . \, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_3 = L_{hx}/ D_c$

$\pi_5 = (P_{capin} \, . \, D_c^2)/(\, \mu_{fc}^2 \, . \, \nu_{fc} \,)$

$\pi_7 = (\Delta T_{sc} \, . \, C_{pfc} \, . \, D_c^2)/(\, \mu_{fc}^2 \, . \, \nu_{fc}^2 \,)$

$\pi_{10} = \nu_{gc} \, / \, \nu_{fc}$

$\pi_{13} = \mu_{gc} / \, \mu_{fc}$

The measured mass flows are compared to the predicted mass flows in Figure 6.3. The deviations ranged from 0.02% to 6.62% (Figure 6.4), while the average deviation was 1.84%. The R^2 of the correlation was 0.983.

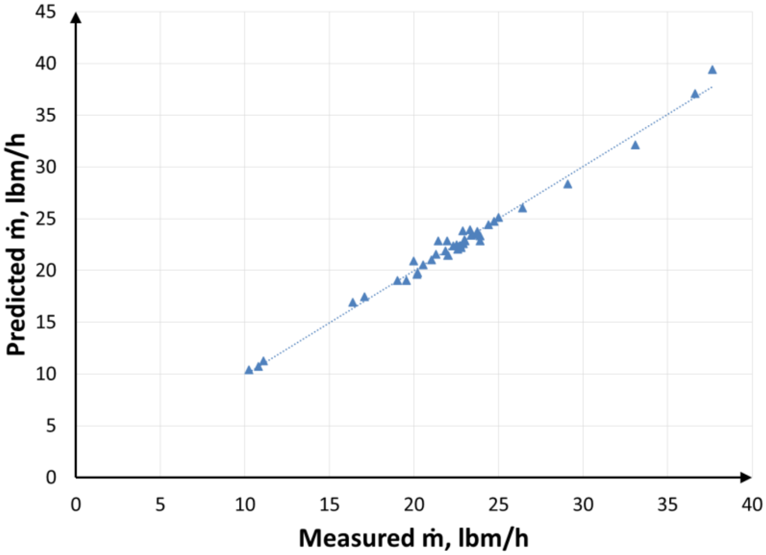

Figure 6.3 R-22: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

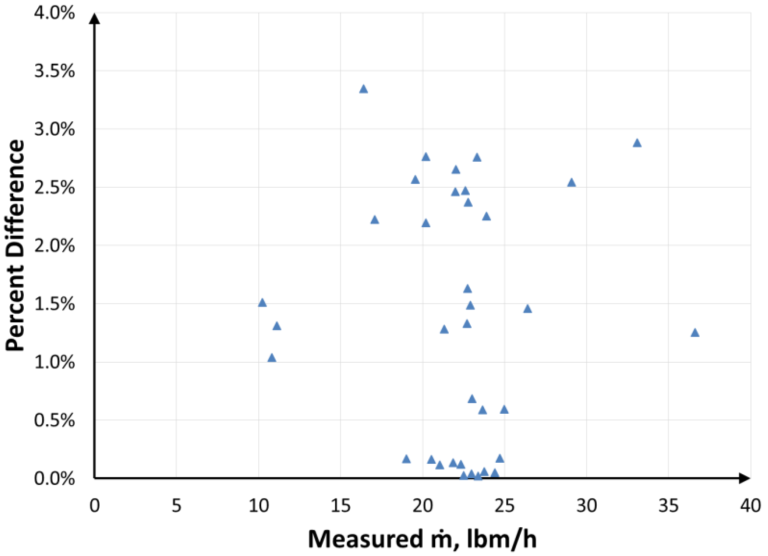

Figure 6.4 R-22: Deviation Distributions for Heat Exchangers with Subcooled Inlet Conditions

6.3. R-410a Correlation for Heat Exchangers

This section describes the correlation to predict the pure R-410a mass flow rate in capillary tubes/suction line heat exchangers, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation. This correlation was formulated from the database for R-410a with subcooled inlet conditions in capillary tube/suction line heat exchangers. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 6.3

Table 6.3 Heat Exchangers Subcooled Inlet Conditions for R-410a.

Operating Variable	Data range
Pcapin	300 to 420 psia
ΔT_{sc}	5 to 30 °F
Psuction	63 to 116 psia
ΔT_{sh}	3 to 43 °F

The final correlation to predict the mass flow of R-410a through capillary tube heat exchangers with subcooled conditions is shown in Equation 6.3.

$$\pi_9=10.0867 * \pi_1^{-0.4420} * \pi_5^{0.4002} * \pi_7^{-0.1273} * \pi_8^{0.05038} * \pi_{10}^{-0.2482} \qquad (6.3)$$

where $\pi_9 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_5 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_7 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

$\pi_8 = (\Delta T_{sh} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

$\pi_{10} = \nu_{gc} / \nu_{fc}$

The measured mass flows are compared to the predicted mass flows in Figure 6.5. The deviations ranged from 0.04% to 6.34% (Figure 6.6), while the average deviation was 1.27%. The R^2 of the correlation was 0.982.

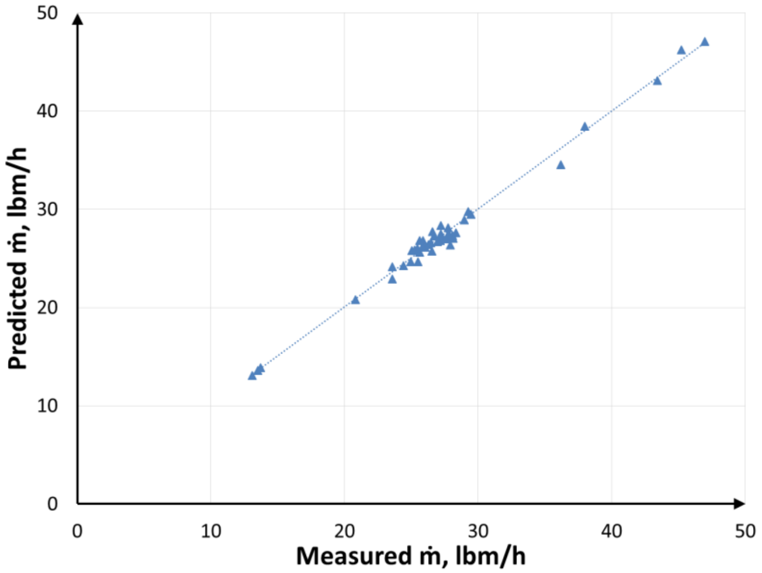

Figure 6.5 R-410a: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

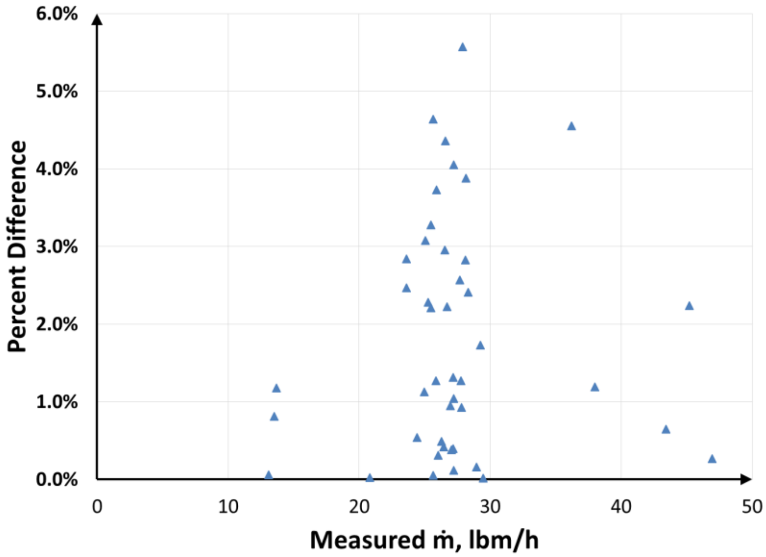

Figure 6.6 R-410a: Deviation Distributions for Heat Exchangers with Subcooled Inlet Conditions

6.4. R-600a Correlation for Heat Exchanger

This section describes the correlation to predict the pure R-600a mass flow rate in capillary tubes/suction line heat exchangers, which was obtained by applying geometry factors, fluid condition effects, and fluid properties to the parameters in the Buckingham Pi Theorem equation. This correlation was formulated from the database for R-600a with subcooled inlet conditions in capillary tube/suction line heat exchangers. Some important condition ranges for the refrigerant at the capillary tube inlet are listed in Table 6.4

Table 6.4 Heat Exchangers Subcooled Inlet Conditions for R-600a.

Operating Variable	Data range
Pcapin	60 to 100 psia
ΔT_{sc}	5 to 35 °F
Psuction	10 to 21 psia
ΔT_{sh}	5 to 45 °F

The final correlation to predict the mass flow of R-600a through capillary tube heat exchangers with subcooled conditions is shown in Equation 6.4.

$$\pi_9 = 0.003545 * \pi_1^{-0.4615} * \pi_3^{0.1107} * \pi_5^{0.6757} * \pi_{10}^{0.3496} * \pi_{15}^{-1.5772} \tag{6.4}$$

where $\pi_9 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_3 = L_{hx}/ D_c$

$\pi_5 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_{10} = \nu_{gc} / \nu_{fc}$

$\pi_{15} = C_{pgc} / C_{pfc}$

The measured mass flows are compared to the predicted mass flows in Figure 6.7. The deviations ranged from 0.02% to 8.56% (Figure 6.8), while the average deviation was 2.95%. The R^2 of the correlation was 0.951.

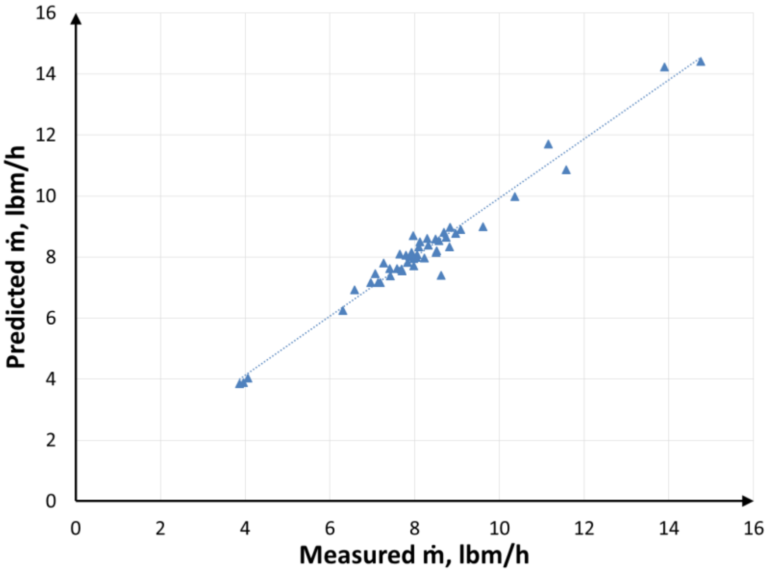

Figure 6.7 R-600a: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

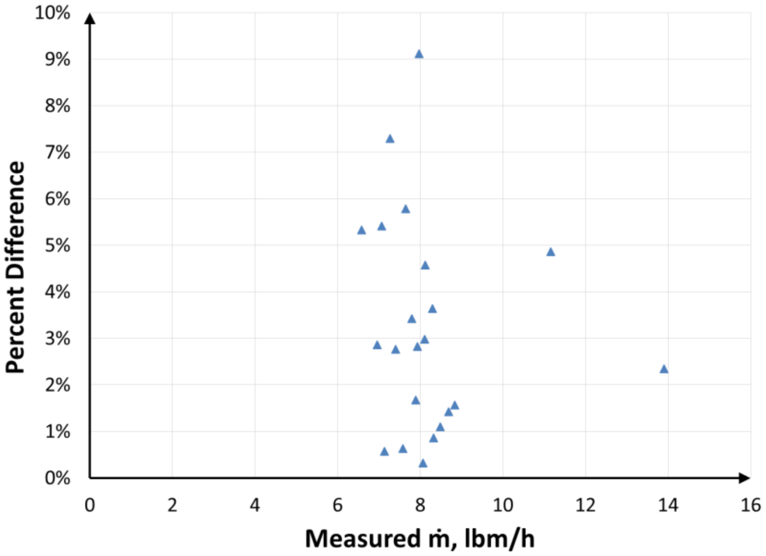

Figure 6.8 R-600a: Deviation Distributions for Heat Exchangers with Subcooled Conditions

CHAPTER VII

GENERALIZED CORRELATIONS

This chapter presents the generalized correlations to predict the mass flows for both adiabatic capillary tubes and capillary tubes/suction line heat exchangers. These two correlations are regressions of non-dimensional parameters including geometry factors, fluid condition effects, and fluid properties based on the Buckingham Pi Theorem. A more detailed discussion of this method has been presented in Chapter 3.

7.1. Generalized Correlations for Adiabatic Capillary Tubes

The generalized correlations predict the mass flow through adiabatic capillary tubes for several different refrigerants. The data base for R-134a, R-22, and R-410a was used to create the correlations, while the data base of R-152a was used to verify the correlations. The correlations were developed for both subcooled inlet conditions and quality inlet conditions.

7.1.1. Correlation for The Subcooled Inlet Condition

This correlation was formulated from the database for R-134a, R-22, and R-410a with subcooled inlet conditions in adiabatic capillary tubes.

The final generalized correlation to predict the refrigerant mass flow through adiabatic capillary tubes with subcooled inlet conditions is shown in Equation 7.1.

$$\pi_8=4.002 * \pi_1^{-0.497} * \pi_2^{0.378} * \pi_3^{0.369} * \pi_4^{0.569} * \pi_5^{0.179} \tag{7.1}$$

where $\pi_8 = \dot{m}/(D_c . \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_2 = (h_{fgc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

$\pi_3 = D_c\, \sigma/ \nu_{fc}^2\, \mu_{fc}^2$

$\pi_4 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_5 = (\Delta T_{sc} \,.\, C_{pfc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

The measured mass flows are compared to the predicted mass flows in Figure 7.1. The deviations ranged from 0.04% to 6.32% (Figure 7.2) while the average deviation was 1.91%. The R^2 of the correlation was 0.999.

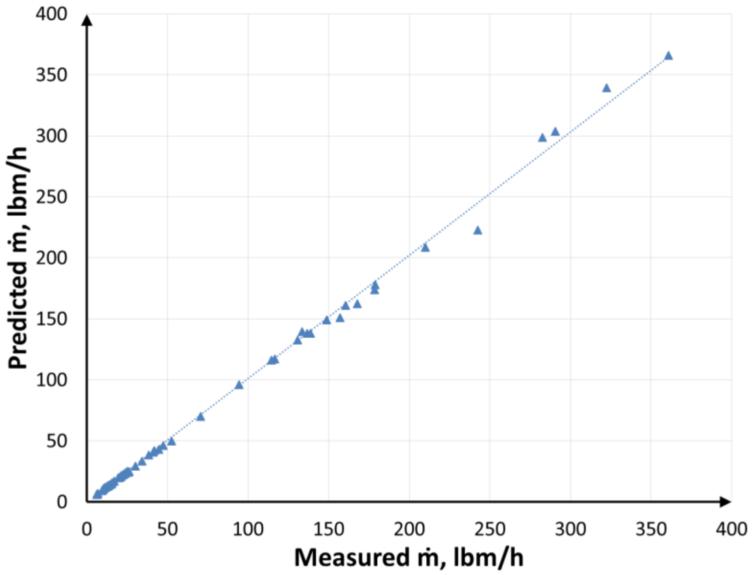

Figure 7.1 Generalized: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

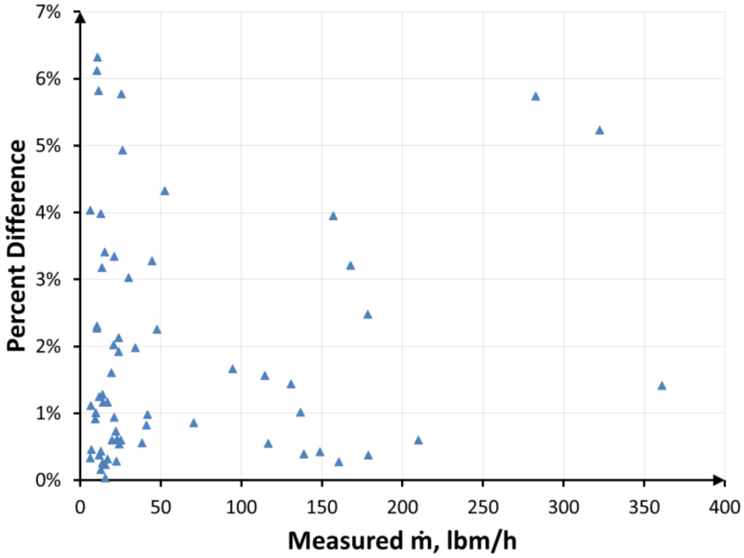

Figure 7.2 Generalized: Deviation Distributions for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

7.1.2. Correlation of Quality Inlet Situation

This correlation was formulated from the database for R-134a, R-22, and R-410a with quality inlet conditions in adiabatic capillary tubes.

The final generalized correlation predicts the refrigerant mass flow through adiabatic capillary tubes with quality conditions as shown in Equation 7.2.

$$\pi_8 = 178.612 * \pi_1^{-0.6685} * \pi_2^{-0.513} * \pi_4^{0.369} * \pi_5^{-0.159} \tag{7.2}$$

where $\pi_8 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_2 = (h_{fgc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

$\pi_4 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_5 = x$

The measured mass flows are compared to the predicted mass flows in Figure 7.3. The deviations ranged from 0.06% to 21.02% (Figure 7.4) while the average deviation was 4.89%. The R^2 of the correlation was 0.993.

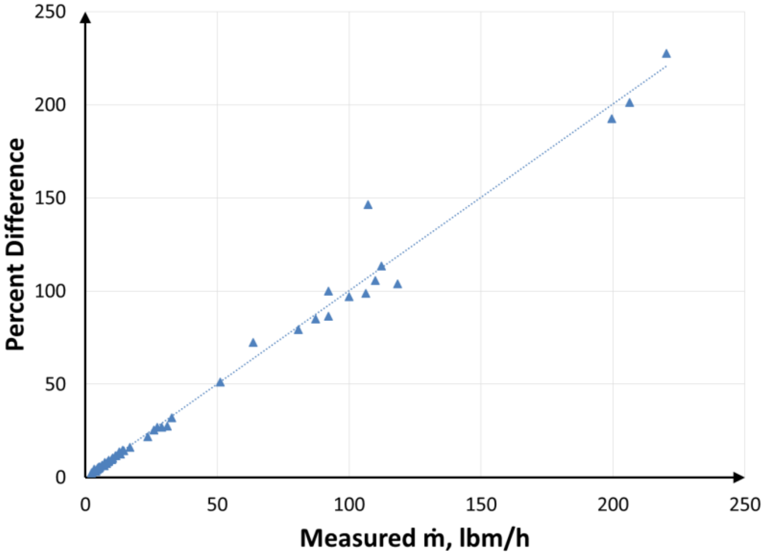

Figure 7.3 Generalized: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Quality Inlet Conditions

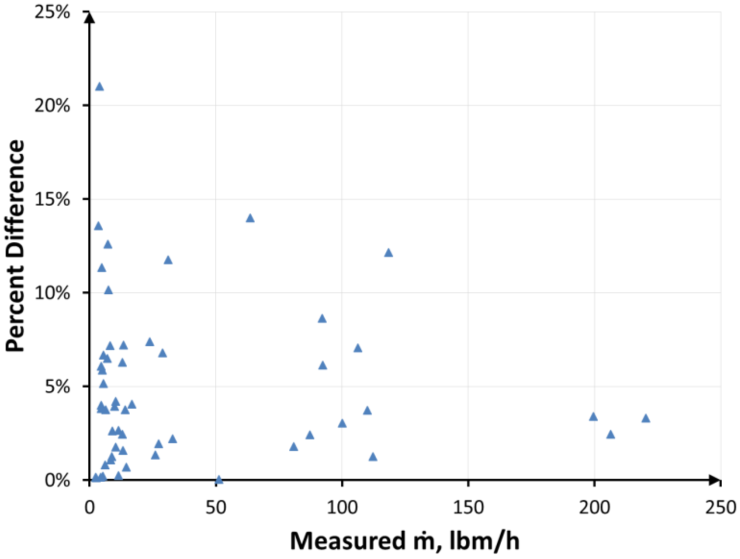

Figure 7.4 Generalized: Deviation Distributions for Adiabatic Capillary Tubes with Quality Inlet Conditions

7.1.3. R-152a Verification

The verification with R-152a data confirmed that the correlations can be applied to new refrigerants that were not used to develop the correlations. Specifically, the database for R-152a was not used to develop Equations 7.1 and 7.2; therefore, it served as new data to verify Equations 7.1 and 7.2.

The R-152a test data with subcooled inlet conditions was applied to Equation 7.1, and the measured mass flows are compared to the predicted mass flows in Figure 7.5. The deviations ranged from 0.15% to 11.72% (Figure 7.6) and the average deviation was 4.23%.

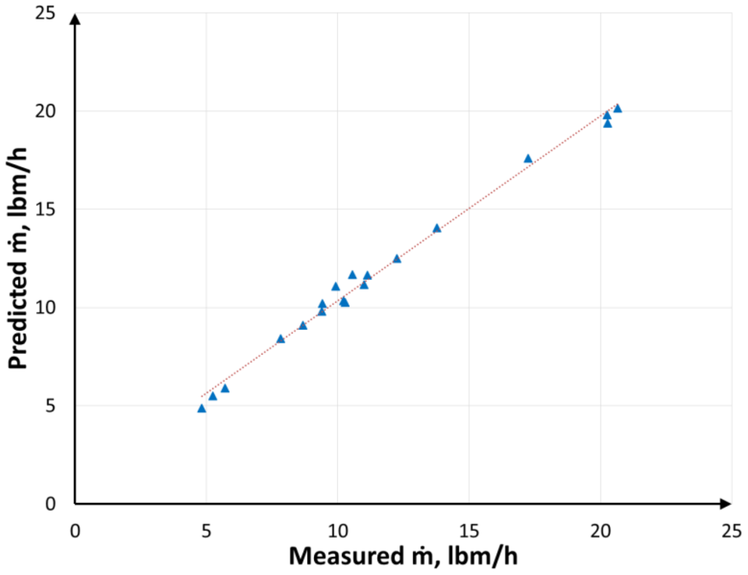

Figure 7.5 R-152a: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

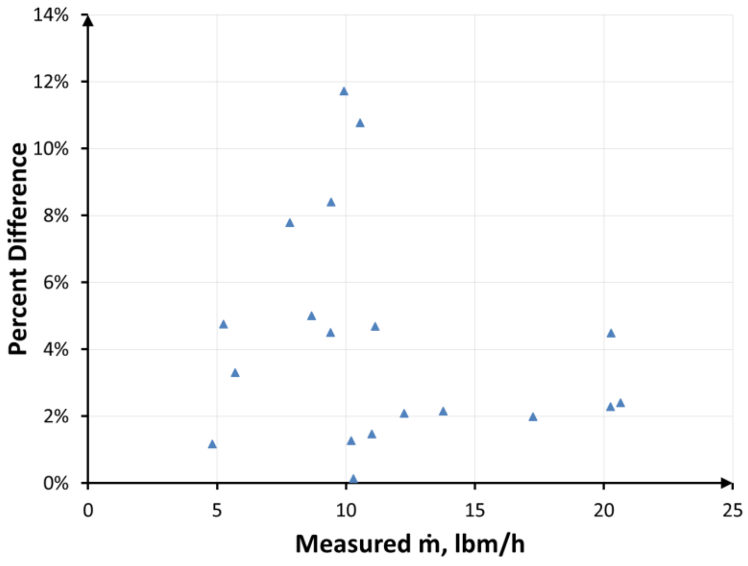

Figure 7.6 R-152a: Deviation Distributions for Adiabatic Capillary Tubes with Subcooled Conditions

The test data of R-152a with quality inlet conditions was applied to Equation 7.1, and the measured mass flows are compared to the predicted mass flows in Figure 7.7. The deviations ranged from 14.39 % to 21.24 % (Figure 7.8) and the average deviation was 17.53 %.

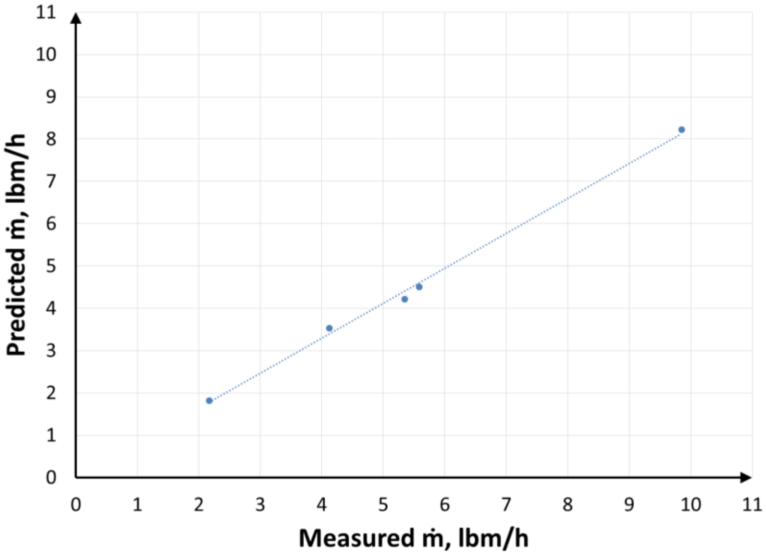

Figure 7.7 R-152a: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Quality Inlet Conditions

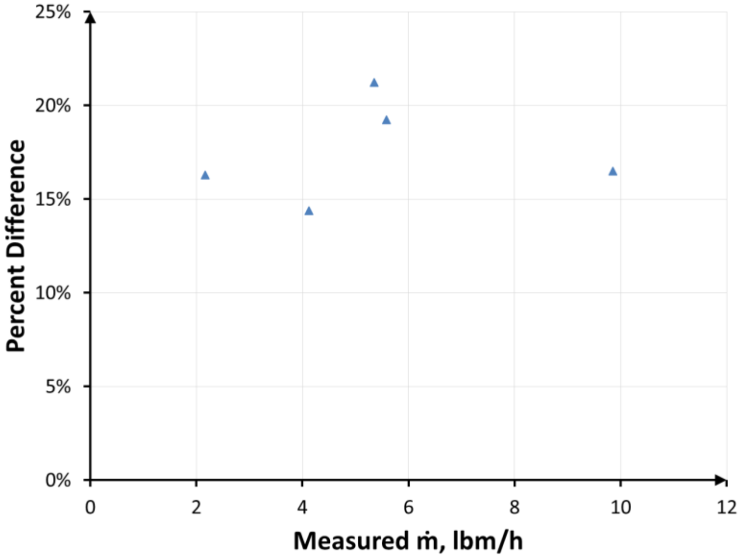

Figure 7.8 R-152a: Deviation Distributions for Adiabatic Capillary Tubes with Quality Inlet Conditions

7.2. Generalized Correlation for Heat Exchanger

The generalized correlations predict the mass flow through a capillary tube/suction line heat exchanger for several different refrigerants. The database for R-134a, R-22, R-410a, and R-600a were used to create the correlations, while the database for R-152a was used to verify the correlations. The correlations were developed for subcooled inlet conditions.

7.2.1. Correlation for The Subcooled Inlet Condition

This correlation was formulated according to R-134a, R-22, R-410a, and R600a test data with subcooled inlet conditions in capillary tube/suction line heat exchangers.

The final generalized correlation is to predict the refrigerant mass flow through a capillary tube/suction line heat exchanger with subcooled inlet conditions as shown in Equation 7.3.

$$\pi_9 = 0.2307 * \pi_1^{-0.5027} * \pi_3^{0.07255} * \pi_5^{0.9258} * \pi_{12}^{-0.3293} * \pi_{13}^{-0.7258} \qquad (7.3)$$

where $\pi_9 = \dot{m}/(D_c \,.\, \mu_{fc})$

$\pi_1 = L_c / D_c$

$\pi_3 = L_{hx}/ D_c$

$\pi_5 = (P_{capin} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc})$

$\pi_{12} = (h_{fgc} \,.\, D_c^2)/(\mu_{fc}^2 \,.\, \nu_{fc}^2)$

$\pi_{13} = \mu_{gc}/ \mu_{fc}$

The measured mass flows are compared to the predicted mass flows in Figure 7.9. The deviations ranged from 0.03% to 14.66% (Figure 7.10), while the average deviation was 2.47%. The R^2 of the correlation was 0.996.

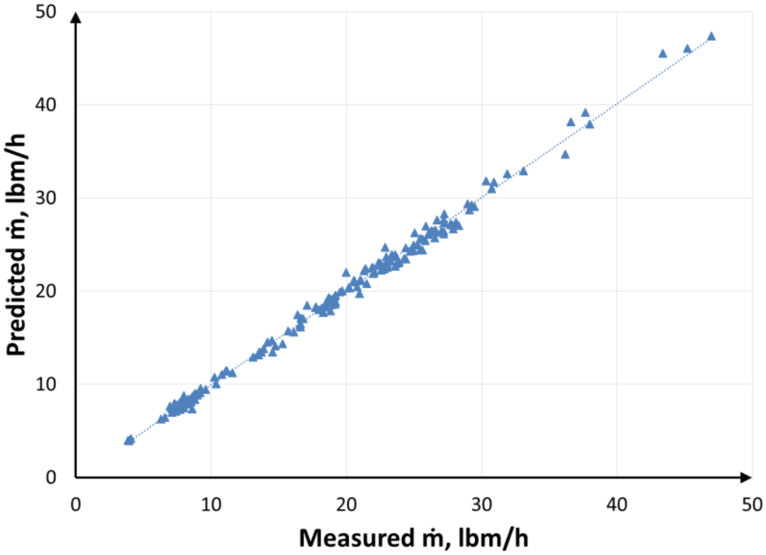

Figure 7.9 Generalized: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

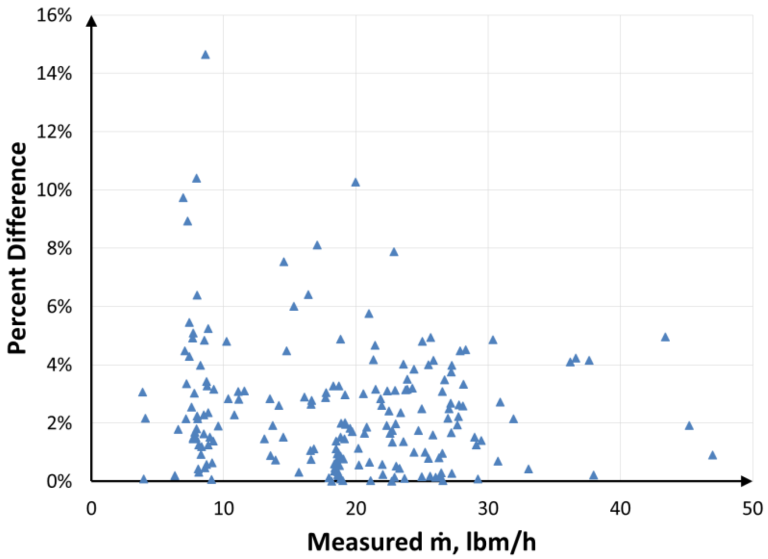

Figure 7.10 Generalized: Deviation Distributions for Heat Exchangers with Subcooled Inlet Conditions

7.2.2. R-152a Verification

The verification with new data confirmed the correlations can apply to new refrigerants which were not used to develop the correlations. The database for R-152a was not used to develop Equation 7.3; therefore, it served as new data to verify Equation 7.3.

The R-152a test data with subcooled inlet conditions applied to Equation 7.3. The measured mass flows are compared to the predicted mass flows in Figure 7.11. The deviations ranged from 1.15% to 12.55% (Figure 7.12) and the average deviation was 5.27%.

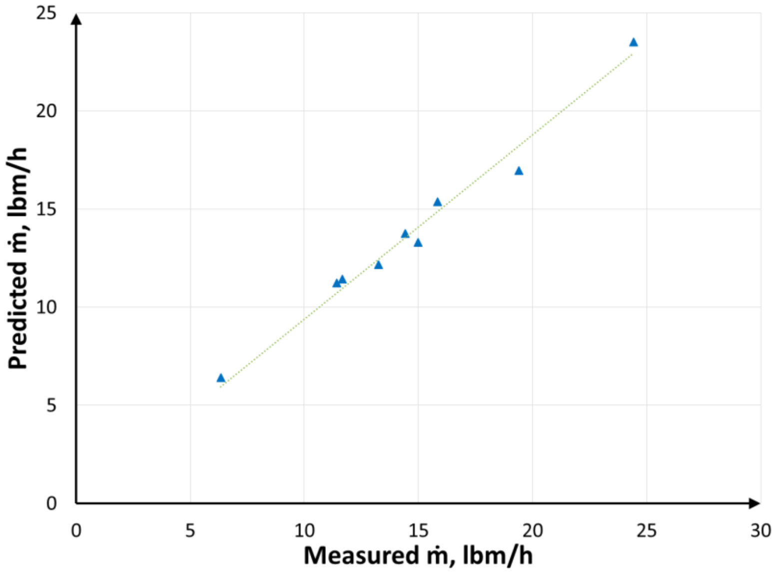

Figure 7.11 R-152a: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

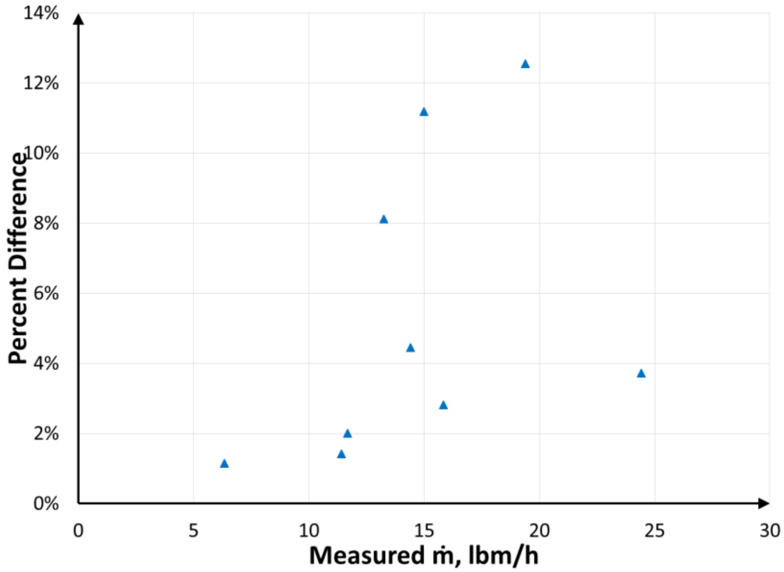

Figure 7.12 R-152a: Deviation Distributions for Heat Exchangers with Subcooled Inlet Conditions

CHAPTER VIII

CORRELATION COMPARISON

In this chapter, the correlations developed in this thesis are compared to the correlations developed in two previous ASHRAE studies, namely 1. “Adiabatic Capillary Tube Performance with Alternative Refrigerants” RP-762 ASHRAE Final Report 1995 by Duane A.Wolf, Robert R. Bittle and Michael B. Pate, and 2. “Capillary Tube/Suction Line Heat Exchangers Performance with Alternative Refrigerants” 948-RP ASHRAE Final Report 2002 by Duane A. Wolf and Michael B. Pate,

8.1. Coefficient Comparison

The newly developed correlation coefficients were compared with the correlation coefficients from previous ASHRAE reports. These dimensionless correlations were developed based on geometry factors, fluid condition effects, and fluid properties. The Pi terms and coefficients changed for each refrigerant, due to the variation of the fluid properties from the different databases over a period of time. The coefficients for adiabatic capillary tubes and capillary tube/suction line heat exchangers are listed in Tables 8.1, 8.2, 8.3.

In the case of adiabatic capillary tubes with subcooled inlet conditions, the Pi terms did not change for R-22 and R-410a correlations, the number of Pi terms increased to four from three for R-134a correlations and decreased from six to five for the general correlation. The coefficient comparison for adiabatic capillary tubes with subcooled inlet conditions is listed in Table 8.1.

An additional study was done to compare the results of using the same Pi terms for R-134a as were used for R-22 and R-410a. The result is Equation 8.1.

$$\pi 8=0.02117* \pi_1^{-0.412}*\pi_4^{0.475}* \pi_5^{0.189} \tag{8.1}$$

It can be observed that the Pi term exponents for R-134a in Equation 8.1 are similar to the old values shown in Table 8.1; however, the intercept is different.

Table 8.1 The Coefficient Comparison for Adiabatic Capillary Tube with Subcooled Inlet Condition

	R-134a		R-22		R-410a		General	
	New	Old	New	Old	New	Old	New	Old
Intercept	0.0176	0.0129	0.4360	0.4763	0.2809	0.3762	4.002	1.893
π_1	-0.5194	-0.387	-0.449	-0.447	-0.513	-0.52	-0.497	-0.484
π_2							0.378	-0.824
π_3	-1.567						0.369	
π_4	1.354	0.492	0.396	0.35	0.405	0.423	0.569	1.369
π_5		0.187	0.166	0.206	0.192	0.17	0.179	0.0187
π_6								0.773
π_7	1.629							0.265

In the case of adiabatic capillary tubes with quality inlet conditions, the Pi terms did not change for R-134a, R-22 and R-410a correlations, the number of Pi terms decreased from six to four for the general correlation. The coefficient comparison for adiabatic capillary tubes with quality inlet conditions is listed in Table 8.2.

Table 8.2 The Coefficient Comparison for Adiabatic Capillary Tubes with Quality Inlet Conditions

	R-134a		R-22		R-410a		General	
	New	Old	New	Old	New	Old	New	Old
Intercept	0.005939	0.006975	0.06899	0.06633	0.1288	3.9123	178.612	187.27
π_1	-0.362	-0.366	-0.353	-0.339	-0.6513	-0.789	-0.6685	-0.635
π_2							-0.513	-0.189
π_3								
π_4	1.663	0.659	0.600	0.6	0.7863	0.569	0.369	0.645
π_5	-0.308	-0.307	-0.0468	-0.0449	-0.1365	-0.136	-0.159	-0.163
π_6								-0.213
π_7								-0.483

In the case of capillary tube/suction line heat exchangers with subcooled inlet conditions, the Pi terms changed for all specific refrigerant correlations. The number of Pi terms decreased from seven to five for the general correlation. The coefficient comparison for heat exchangers with subcooled inlet conditions is listed in Table 8.3.

Table 8.3 The Coefficient Comparison for Heat Exchangers with Subcooled Inlet Conditions

	R-134a		R-22		R-410a		R-600a		General	
	New	Old	New	Old	New	Old	New	Old	New	Old
Intercept	0.6688	0.7028	0.000182	0.07851	10.087	0.5785	0.00355	0.03069	0.2307	0.07602
π_1	-0.6081	-0.576	-0.4750	-0.506	-0.442	-0.4473	-0.4615	-0.37	-0.5027	-0.4583
π_2										
π_3	0.08049	0.0932	0.1896	0.0611		0.04425	0.1107	0.1187	0.07255	0.07751
π_4										
π_5	0.6482	0.6273	0.4544	0.7443	0.4002	0.5989	0.6757	0.6818	0.9258	0.7342
π_6	-0.1125	-0.08078		-0.1548		-0.06415		-0.0267		-0.1204
π_7	-0.0497	0.0434	-0.1620	0.0869	-0.1273	0.0637		0.05038		0.03774
π_8		-0.01631		-0.0369	0.05038	-0.04557		-0.06939		-0.04085
π_{10}			-2.7435		-0.2482		0.3496			
π_{11}										0.1768
π_{12}									-0.3293	
π_{13}			-5.548						-0.7258	
π_{14}										
π_{15}							-1.5772			

8.2. Accuracy Analysis

The accuracy of the newly developed correlation and the old correlation in ASHRAE reports was compared in this section. The average deviation, the maximum and the minimum deviation were all used to analyze the correlation accuracy.

In the case of the adiabatic capillary tube with subcooled inlet conditions, the deviation range of newly developed correlations was smaller than that of the old correlations in ASHRAE reports. The average deviations of newly developed specific refrigerant correlations ranged from 1.65% to 2.51%, while average deviations of correlations published in the ASHRAE reports ranged from 3.38% to 9.29%. The new correlations provided better prediction compare to the old correlation for the mass flow in an adiabatic capillary tube with subcooled inlet conditions. Table 8.4 shows the deviation comparison.

Table 8.4 Deviation Comparison for Adiabatic Capillary Tube with Subcooled Inlet Conditions

Correlation Types	Old Correlation			New Correlation		
	Average Deviation	Max Deviation	Min Deviation	Average Deviation	Max Deviation	Min Deviation
R-134a	5.07%	11.65%	0.48%	1.65%	3.50%	0.29%
R-22	3.38%	6.70%	0.18%	2.51%	6.16%	0.01%
R-410a	9.29%	12.80%	5.17%	1.75%	3.27%	0.15%
General	5.19%	13.02%	0.65%	1.91	6.32%	0.04%

In case of the adiabatic capillary tubes with quality inlet conditions, the deviation range of newly developed correlations was smaller than that of the old correlations contained in ASHRAE reports. The old correlation for R-410a published in ASHRAE reports was not available with the current fluid properties database. For the generalized study, the newly developed generalized correlation was found more accurate than the old generalized correlation. Table 8.5 shows the deviation comparison.

Table 8.5 Deviation Comparison for Adiabatic Capillary Tube with Quality Inlet Condition

Correlation Types	Old Correlation			New Correlation		
	Average Deviation	Max Deviation	Min Deviation	Average Deviation	Max Deviation	Min Deviation
R-134a	6.84%	17.48%	1.13%	6.30%	13.50%	0.44%
R-22	5.96%	14.80%	0.35%	3.82%	8.88%	0.10%
R-410a	Not available any more	Not available any more	Not available any more	4.61%	12.87%	0.86%
General	13.50%	43.55%	0.17%	4.89%	21.02%	0.06%

In the case of the capillary tube/suction line heat exchangers with subcooled inlet conditions, the average deviations of newly developed specific refrigerant correlations ranged from 1.27% to 3.31%, while the average deviations published in ASHRAE reports ranged from 2.9% to 4.19%. The newly developed correlations performed a little bit better than the old correlations. The old generalized correlation in ASHRAE reports did not predict mass flow very well, with the average deviation being 35.95%. In contrast, the new generalized correlations yielded an average deviation of 2.42% for the mass flow in capillary tube/suction line heat exchangers with subcooled inlet conditions. Table 8.6 shows the deviation comparison.

Table 8.6 Deviation Comparison for Heat Exchangers with Subcooled Inlet Conditions

Correlation Types	Old Correlation			New Correlation		
	Average Deviation	Max Deviation	Min Deviation	Average Deviation	Max Deviation	Min Deviation
R-134a	2.90%	6.30%	0.17%	2.29%	6.51%	0.10%
R-22	2.37%	13.6%	0.25%	1.84%	6.62%	0.02%
R-410a	2.05%	4.83%	0.15%	1.27%	6.34%	0.04%
R-600a	4.19%	12.26%	0.15%	3.31%	14.16%	0.15%
General	35.95%	48.02%	26.88%	2.42%	14.66%	0.00%

CHAPTER IX

GENERALIZED CORRELATION SIMPLIFICATION

This chapter presents a generalized correlation simplification process in that generalized correlations with reduced numbers of Pi-terms were developed to predict the refrigerant mass flow. Both adiabatic capillary tubes and capillary tube/suction line heat exchangers are included.

9.1. Generalized Correlation Simplification for Adiabatic Capillary Tube

This section describes the generalized correlation simplification process for adiabatic capillary tubes. The simplified correlations were developed for both subcooled and quality inlet conditions. The accuracy of each correlation was analyzed.

9.1.1. Generalized Simplified Correlations

The process of correlation simplification is to reduce Pi terms based on the P-value of each Pi term. The Pi term that has the highest P-value was excluded from the correlation. Correlations were developed to include a varied number of Pi terms from 7 to 1.

The correlations that predict the refrigerant mass flows through adiabatic capillary tubes with subcooled inlet conditions are shown in Table 9.1, while quality inlet conditions are shown in Table 9.2.

Table 9.1 Generalized Simplified Correlations for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

Model Types	Correlation
7 Pi Terms	$\pi_8=3.4025 * \pi_1^{-0.486} * \pi_2^{0.437} * \pi_3^{0.374} * \pi_4^{0.643} * \pi_5^{0.169} * \pi_6^{0.0435} * \pi_7^{0.0514}$
6 Pi Terms	$\pi_8=3.648 * \pi_1^{-0.492} * \pi_2^{0.421} * \pi_3^{0.354} * \pi_4^{0.634} * \pi_5^{0.168} * \pi_6^{0.0746}$
5 Pi Terms	$\pi_8=4.002 * \pi_1^{-0.497} * \pi_2^{0.378} * \pi_3^{0.369} * \pi_4^{0.569} * \pi_5^{0.1795}$
4 Pi Terms	$\pi_8=1.789 * \pi_1^{-0.526} * \pi_2^{0.194} * \pi_4^{0.557} * \pi_5^{0.198}$
3 Pi Terms	$\pi_8=0.036 * \pi_1^{-0.442} * \pi_4^{0.469} * \pi_5^{0.185}$
2 Pi Terms	$\pi_8=0.575 * \pi_1^{-0.467} * \pi_4^{0.569}$
1 Pi Terms	$\pi_8=5.58 * 10^{-5} * \pi_4^{-0.791}$

Table 9.2 Generalized Simplified Correlations for Adiabatic Capillary Tubes with Quality Inlet Conditions

Model Types	Correlation
7 Pi Terms	$\pi_8=353.1 * \pi_1^{-0.499} * \pi_2^{-4.37} * \pi_3^{-0.722} * \pi_4^{5.27} * \pi_5^{-0.156} * \pi_6^{4.828} * \pi_7^{0.473}$
6 Pi Terms	$\pi_8=725.86 * \pi_1^{-0.5497} * \pi_2^{-4.277} * \pi_3^{-0.816} * \pi_4^{5.2} * \pi_5^{-0.154} * \pi_6^{5.152}$
5 Pi Terms	$\pi_8=186.7 * \pi_1^{-0.665} * \pi_2^{-0.532} * \pi_3^{0.0318} * \pi_4^{0.978} * \pi_5^{0.159}$
4 Pi Terms	$\pi_8=178.6 * \pi_1^{-0.669} * \pi_2^{0.513} * \pi_4^{0.975} * \pi_5^{-0.159}$
3 Pi Terms	$\pi_8=0.00138 * \pi_1^{-0.387} * \pi_4^{0.742} * \pi_5^{0.172}$
2 Pi Terms	$\pi_8=0.00164 * \pi_1^{-0.499} * \pi_4^{0.785}$
1 Pi Terms	$\pi_8=1.57 * 10^{-7} * \pi_4^{0.996}$

9.1.2. Accuracy Analysis

The R^2 and deviations served as a demonstration of the correlation accuracy. The R^2, the average deviation, the maximum deviation and the minimum deviation are shown in Table 9.3 for subcooled inlet conditions and in Table 9.4 for quality inlet conditions.

Table 9.3 R^2 and Deviations of General Simplified Correlations for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

Correlation Type	R Square	Average Deviation	Max Deviation	Min Deviation
7 Pi Terms	0.99900	1.87%	5.91%	0.02%
6 Pi Terms	0.99900	1.90%	6.15%	0.01%
5 Pi Terms	0.99898	1.91%	6.32%	0.04%
4 Pi Terms	0.99875	2.06%	6.73%	0.05%
3 Pi Terms	0.99787	3.16%	11.47%	0.004%
2 Pi Terms	0.98720	7.29%	16.05%	0.32%
1 Pi Terms	0.91440	21.44%	68.83%	0.36%

Table 9.4 R^2 and Deviations of General Simplified Correlations for Adiabatic Capillary Tubes with Quality Inlet Conditions

Correlation Type	R Square	Average Deviation	Max Deviation	Min Deviation
7 Pi Terms	0.9941	4.13%	13.50%	0.00%
6 Pi Terms	0.9939	5.54%	36.23%	0.06%
5 Pi Terms	0.9931	5.66%	35.09%	0.08%
4 Pi Terms	0.9931	5.98%	36.60%	0.16%
3 Pi Terms	0.9889	5.97%	36.67%	0.06%
2 Pi Terms	0.9751	7.83%	40.34%	0.00%
1 Pi Terms	0.9123	11.83%	67.69%	0.03%

As the R^2 became lower, the average deviation became larger, and the range of deviation also became larger with the reduction of the Pi-term numbers. Figure 9.1 and

Figure 9.3 show the measured mass flow versus predicted mass flow, and Figure 9.2 and Figure 9.4 show the deviation distribution.

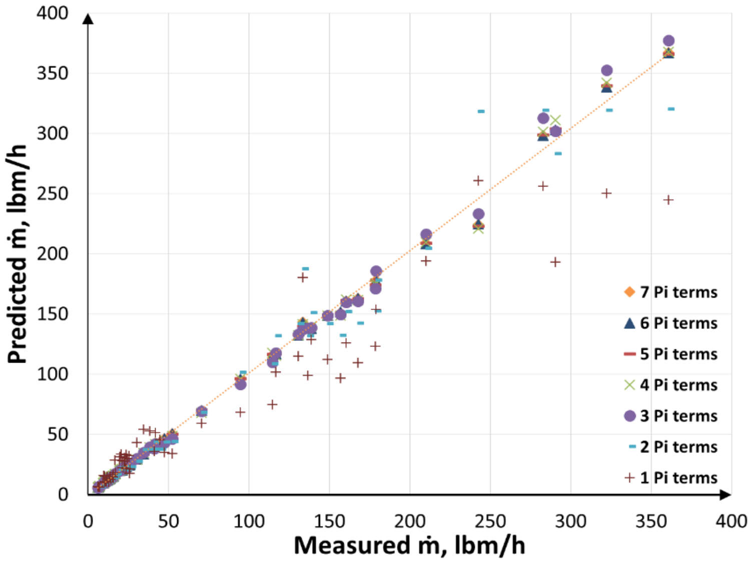

Figure 9.1 General Simplified Correlations: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Subcoobled Inlet Conditions

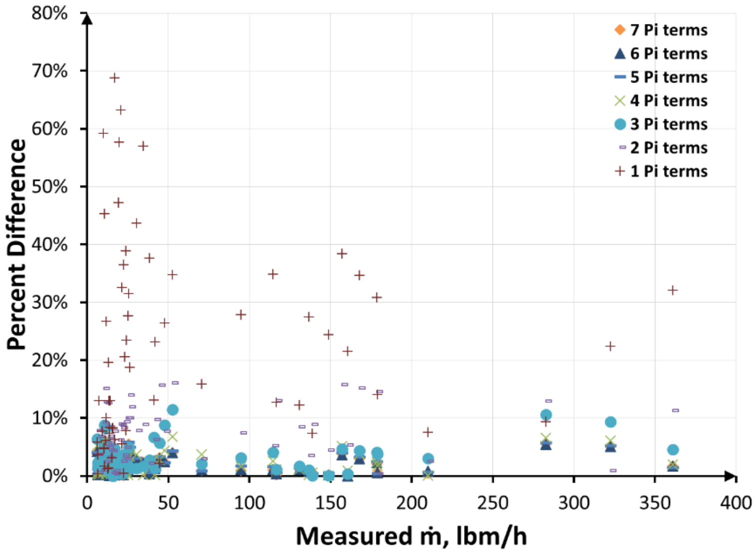

Figure 9.2 General Simplified Correlations: Deviation Distributions for Adiabatic Capillary tubes with Subcooled Inlet Conditions

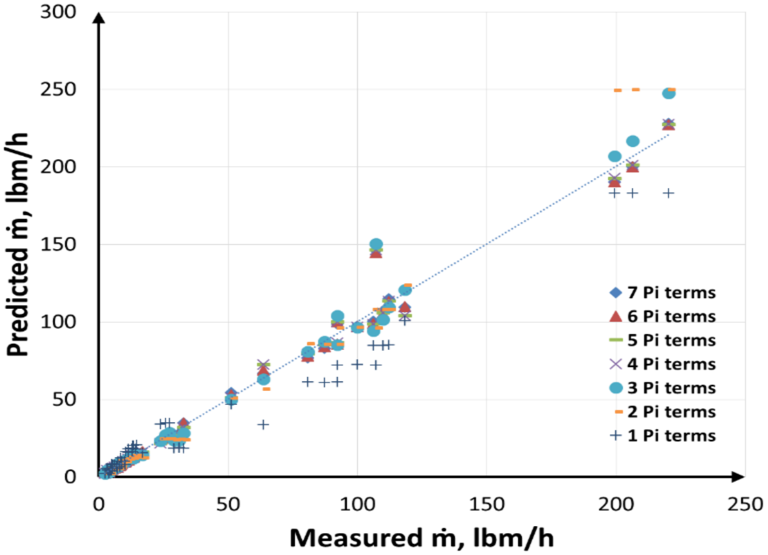

Figure 9.3 General Simplified Correlations: Measured Mass Flows versus Predicted Mass Flows for Adiabatic Capillary Tubes with Quality Inlet Conditions\

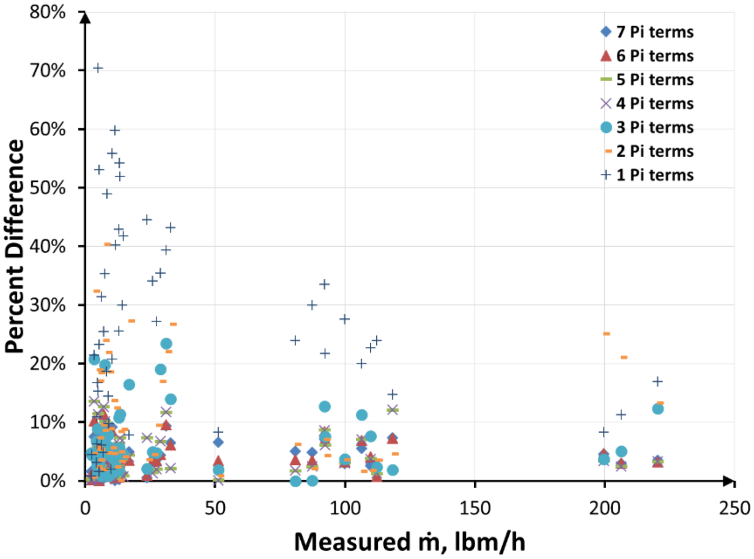

Figure 9.4 General Simplified Correlations: Deviation Distributions for Adiabatic Capillary Tubes with Quality Inlet Conditions

The R^2 distribution and the average deviation distribution are shown in Figure 9.5 and Figure 9.6. When the number of pi-terms was more than four, the R^2 stayed at a high level, and the average deviation stay at a low value, while being stable.

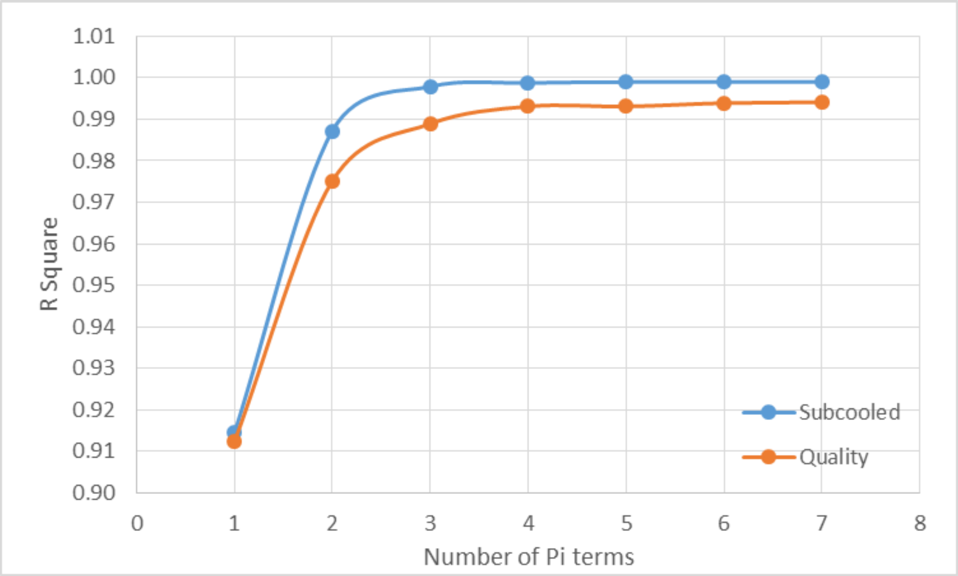

Figure 9.5 General Simplified Correlations: R^2 Distribution

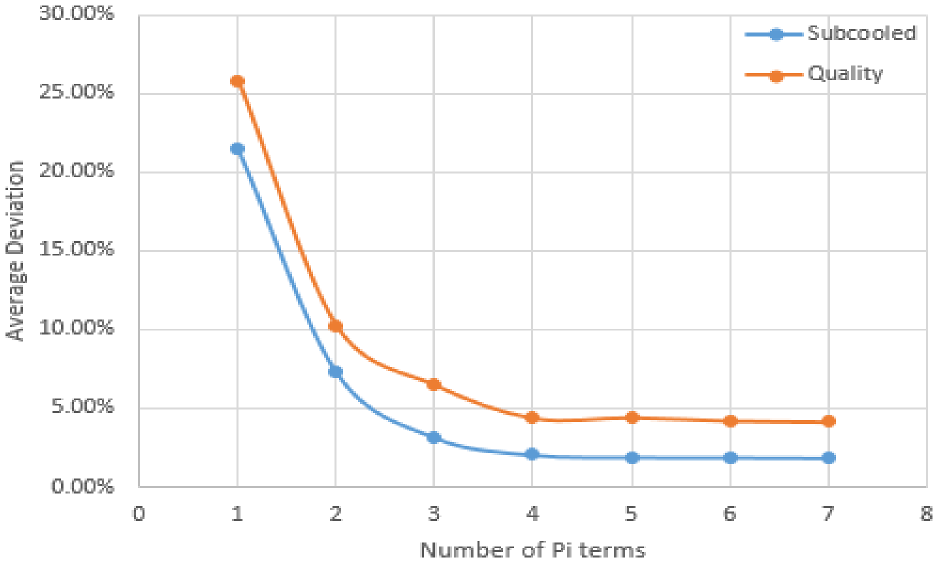

Figure 9.6 General Simplified Correlations: Average Deviation Distribution

9.2. Generalized Correlation Simplification for Heat Exchanger

This section describes the process of generalized correlation simplification for capillary tubes/suction line heat exchangers with subcooled inlet conditions. The accuracy of each correlation was analyzed by comparison with the database.

9.2.1. General Simplified Correlations

The process of correlation simplification is to reduce Pi terms based on the P-value of each Pi term. The Pi term that had the highest P-value was excluded from the correlation. Correlations were developed to include a varied number of Pi terms from 14 to 1.

The correlations predict the refrigerant mass flows in adiabatic capillary tubes with subcooled inlet conditions are shown in Table 9.5,

Table 9.5 Generalized Simplified Correlations for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

Model Types	Correlation
14 Pi Terms	$\pi_9=0.8045* \pi_1^{-0.5027}* \pi_2^{-0.0055}* \pi_3^{0.06883} *\pi_4^{-0.03506} * \pi_5^{0.8176} * \pi_6^{-0.03525} * \pi_7^{0.02742} * \pi_8^{-0.02182}* \pi_{10}^{0.002235} * \pi_{11}^{0.2570} *\pi_{12}^{-0.2256} * \pi_{13}^{-0.3548} * \pi_{14}^{0.02575} * \pi_{15}^{-0.03394}$
13 Pi Terms	$\pi_9=0.7552* \pi_1^{-0.5020}* \pi_2^{-0.00523}* \pi_3^{0.06881} *\pi_4^{-0.03421} * \pi_5^{0.8202} * \pi_6^{-0.03609} * \pi_7^{0.02727} * \pi_8^{-0.02225}* \pi_{10}^{-0.00895}* \pi_{11}^{0.2026} *\pi_{12}^{-0.2256} * \pi_{13}^{-0.3815} * \pi_{14}^{0.02628}$
12 Pi Terms	$\pi_9=0.7668* \pi_1^{-0.5021}* \pi_2^{-0.00517}* \pi_3^{0.06872} *\pi_4^{-0.03407} * \pi_5^{0.8270} * \pi_6^{-0.03662} * \pi_7^{0.02605} * \pi_8^{-0.02224}* \pi_{11}^{-0.2436}*\pi_{12}^{-0.2304} * \pi_{13}^{-0.3716} * \pi_{14}^{0.02787}$
11 Pi Terms	$\pi_9=0.6620* \pi_1^{-0.5018}* \pi_2^{-0.00474}* \pi_3^{0.06891} *\pi_4^{-0.03306} * \pi_5^{0.8316} * \pi_6^{-0.03799} * \pi_7^{0.02560} * \pi_8^{-0.02249} *\pi_{12}^{-0.2314} * \pi_{13}^{-0.4118} * \pi_{14}^{0.02215}$

10 Pi Terms	$\pi_9=0.6055* \pi_1^{-0.5021}* \pi_3^{0.06888} *\pi_4^{-0.03346} * \pi_5^{0.8303} * \pi_6^{-0.03807} * \pi_7^{0.02567} * \pi_8^{-0.02250} * \pi_{12}^{-0.2282} * \pi_{13}^{-0.4123} * \pi_{14}^{0.02204}$
9 Pi Terms	$\pi_9=0.7553* \pi_1^{-0.4967}* \pi_3^{0.06853} *\pi_4^{-0.03095} * \pi_5^{0.8488} * \pi_7^{0.02022} * \pi_8^{-0.01759} *\pi_{12}^{-0.2905} * \pi_{13}^{-0.5054} * \pi_{14}^{0.02594}$
8 Pi Terms	$\pi_9=0.4608* \pi_1^{-0.4985} * \pi_3^{0.06823} * \pi_5^{0.8399} * \pi_7^{0.02071} * \pi_8^{-0.01760} *\pi_{12}^{-0.2687} * \pi_{13}^{-0.5106} * \pi_{14}^{0.02508}$
7 Pi Terms	$\pi_9=0.4655* \pi_1^{-0.4988} * \pi_3^{0.06699} * \pi_5^{0.8782} * \pi_8^{-0.01586} *\pi_{12}^{-0.2881} * \pi_{13}^{-0.5702} * \pi_{14}^{0.02376}$
6 Pi Terms	$\pi_9=0.3588* \pi_1^{-0.4947} * \pi_3^{0.06813} * \pi_5^{0.8951} * \pi_8^{-0.01530} *\pi_{12}^{-0.2993} * \pi_{13}^{-0.6518}$
5 Pi Terms	$\pi_9=0.2307* \pi_1^{-0.5027} * \pi_3^{0.07255} * \pi_5^{0.9258} *\pi_{12}^{-0.3293} * \pi_{13}^{-0.7258}$
4 Pi Terms	$\pi_9=1.099* \pi_1^{-0.4992} * \pi_5^{0.9387} *\pi_{12}^{-0.3736} * \pi_{13}^{-0.7037}$
3 Pi Terms	$\pi_9=0.005816* \pi_1^{-0.3898} * \pi_5^{0.6905} * \pi_{13}^{-0.4725}$
2 Pi Terms	$\pi_9=2.1755* \pi_1^{-0.3898} * \pi_5^{0.5400}$
1 Pi Terms	$\pi_8=0.02554* \pi_5^{-0.5495}$

9.2.2. Accuracy Analysis

The R^2 and deviations served as the demonstration of the correlation accuracy. The R^2, the average deviation, the maximum deviation and the minimum deviation are shown in Table 9.6 for subcooled inlet conditions.

Table 9.6 R^2 and Deviations of General Simplified Correlations for Adiabatic Capillary Tubes with Subcooled Inlet Conditions

Correlation Type	R Square	Average Deviation	Max Deviation	Min Deviation
14 Pi Terms	0.996799	2.35%	14.44%	0.05%
13 Pi Terms	0.996798	2.35%	14.42%	0.00%
12 Pi Terms	0.996797	3.63%	15.24%	0.01%
11 Pi Terms	0.996796	3.42%	15.00%	0.00%
10 Pi Terms	0.996794	2.35%	14.41%	0.03%
9 Pi Terms	0.996745	2.38%	14.27%	0.02%
8 Pi Terms	0.996716	2.40%	14.33%	0.06%
7 Pi Terms	0.996584	2.42%	14.62%	0.00%
6 Pi Terms	0.996418	2.42%	14.66%	0.00%
5 Pi Terms	0.996245	2.47%	14.66%	0.03%
4 Pi Terms	0.995323	2.76%	14.59%	0.03%
3 Pi Terms	0.993185	3.55%	13.95%	0.02%
2 Pi Terms	0.988958	4.70%	20.43%	0.01%
1 Pi Terms	0.971226	7.15%	28.20%	0.09%

As the R^2 became lower, the average deviation became larger, and the range of deviation also became larger with the reduction of the Pi-term numbers. Figure 9.7 shows the measured mass flow versus predicted mass flow, and Figure 9.8 shows the deviation distribution.

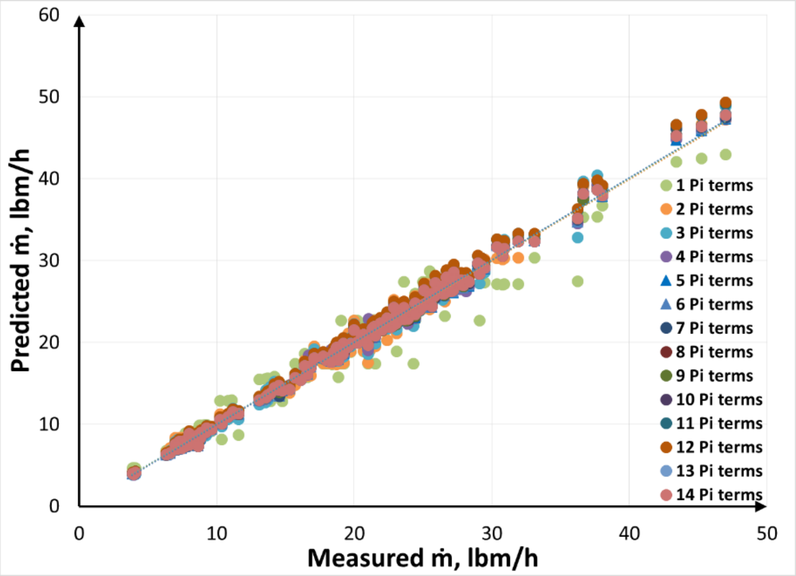

Figure 9.7 General Simplified Correlations: Measured Mass Flows versus Predicted Mass Flows for Heat Exchangers with Subcooled Inlet Conditions

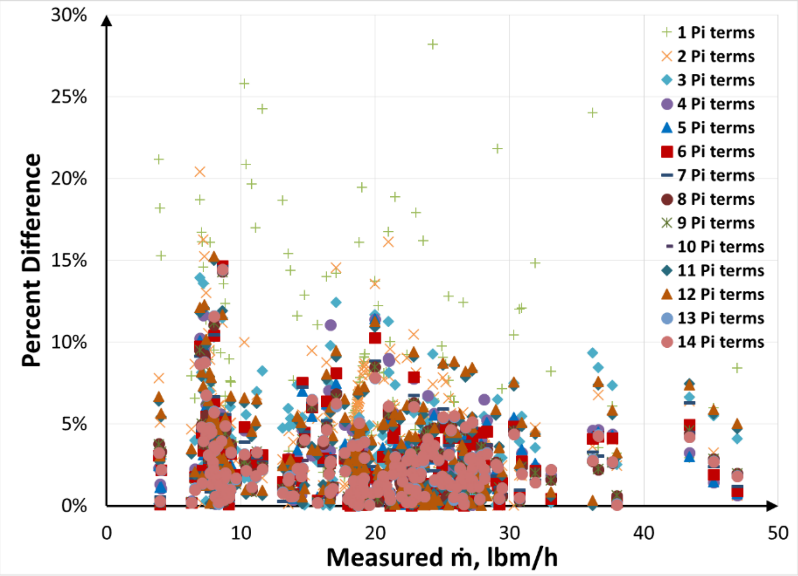

Figure 9.8 General Simplified Correlations: Deviation Distributions for Heat ‘ Exchangers with Subcooled Inlet Conditions

The R^2 distribution and average deviation distribution are shown in Figure 9.9 and Figure 9.10. When the number of Pi-terms are more than four, the R^2 stayed at a high level and average deviation stay at a low value, while being stable.

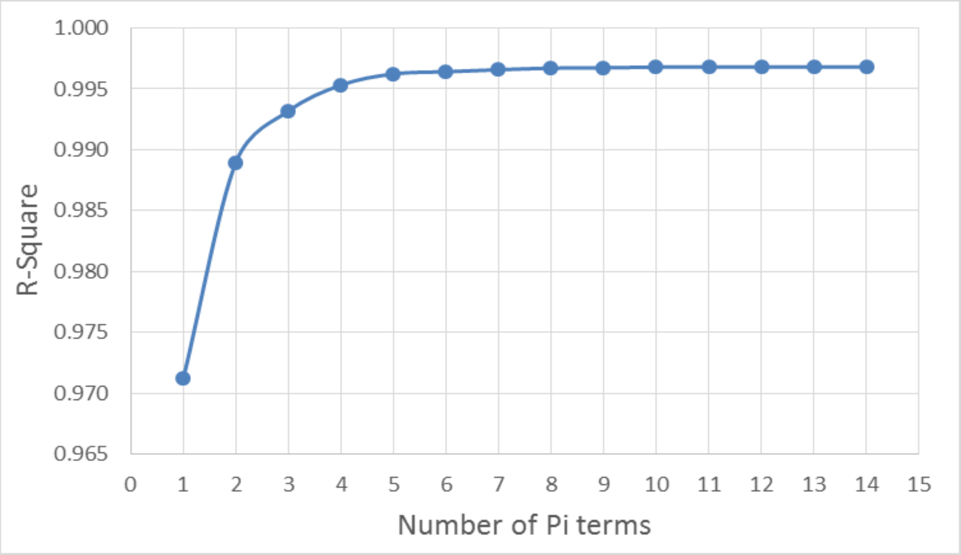

Figure 9.9 General Simplified Correlations: R^2 Distribution

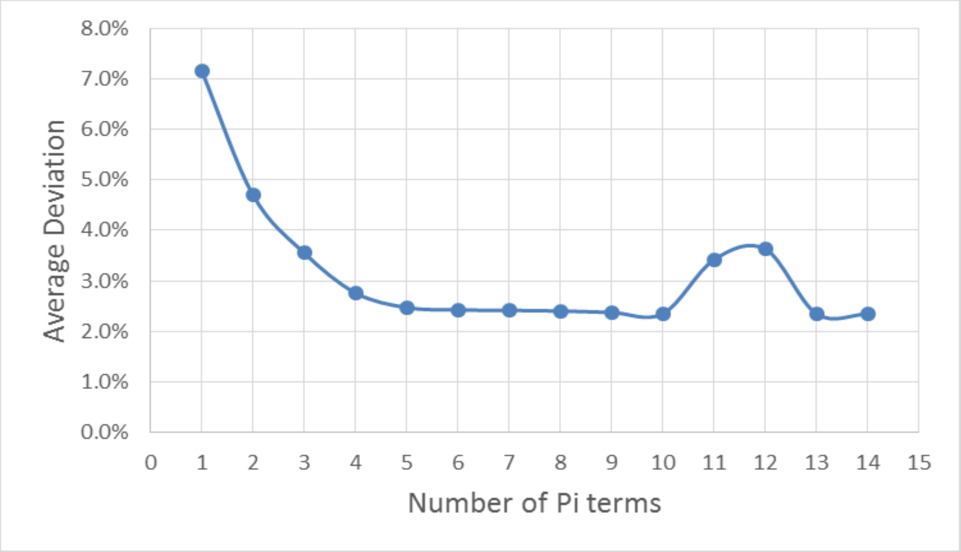

Figure 9.10 General Simplified Correlations: Average Deviation Distribution

CHAPTER X

PI TERMS ANALYSIS

The focus of this chapter is a Pi term analysis to determine if there was sufficient variations in Pi term values obtained from the 26 data points for adiabatic capillary tubes to support a regression analysis. For example, if the 26 Pi term values for any given Pi term were all similar, then the ratio of each Pi term to the average would be close to unity. As result, the Pi term would not have a sufficient variation to be considered in the regression analysis, even though it might be important.

The R-134a data for adiabatic capillary tubes with subcooled inlet conditions were used to calculate the Pi term values for each data point as shown in Table 10.1. The Table 10.1 results were then used to calculate the variation between each Pi term value and the average Pi term value by forming ratios with the average as shown in Table 10.2. An analysis of the minimum and maximum ratios for each Pi term shown at the bottom in Table 10.2 indicates that the original experimental data file resulted in sufficient variations for each of the 8 different Pi terms to validate the regression analysis and the resulting functions.

Additional verification is obtained by comparing the resulting Pi term functions to the Table 10.2minimum and maximum values. In one case the correlation for pure R-134a included π_1, π_3, π_4, π_7, while in a second case the correlation included π_1, π_4, π_5, with both cases performing to a similar accuracy. Furthermore the generalized correlation included π_1, π_2, π_3, π_4, π_5. It can be seen in Table 10.2 that π_5 varied the most, π_7 changed the least, and the rest of them varied to a similar level.Even though π_6, π_7 are not in the generalized equation, they still have sufficient variations when calculated from actual data to have been considered in the regression analysis. In another words, these two Pi terms were not excluded from the function because they were constant over the data file but rather because they were not important. In summary, the data file used in the regression analysis is adequate for determining the functional equations relating Pi terms.

Table 10.1 Pi Term Data for R134a in Adiabatic Capillary Tubes with Subcooled Inlet Conditions

	π_1	π_2	π_3	π_4	π_5	π_6	π_7	π_8
1	3823.529	5.53E+12	226747.4	3.26E+10	7.77E+11	30.45857	14.09386	12715.32
2	3823.529	4.59E+12	210252.7	1.73E+10	5.79E+11	48.03329	17.78367	8784.483
3	5000	2.94E+12	167560.3	1.4E+10	3.9E+11	38.571	15.93702	6864.535
4	3095.238	7.65E+12	270329.9	3.64E+10	1.01E+12	38.85738	15.99712	15637.92
5	3823.529	5.03E+12	219133.2	2.4E+10	6.67E+11	38.55739	15.93429	10500.02
6	3823.529	5.01E+12	218707	1.98E+10	4.41E+11	38.98638	16.02447	8372.679
7	3823.529	5.32E+12	223849.6	2.19E+10	2.43E+11	33.60728	14.84411	8113.053
8	3823.529	5.45E+12	225729	2.73E+10	5.06E+11	31.60181	14.37161	10273.96
9	3823.529	5.79E+12	229726.5	3.03E+10	2.81E+11	26.91523	13.18388	9997.061
10	3823.529	5.34E+12	224212.4	2.2E+10	2.45E+11	33.23698	14.75807	8147.383
11	3823.529	5.79E+12	229705.3	3.55E+10	5.63E+11	26.93468	13.18893	12859.35
12	3823.529	6.23E+12	232616.9	4.04E+10	3.21E+11	22.14647	11.82221	12216.17
13	3095.238	8.28E+12	278522.2	4.14E+10	7.68E+11	31.86647	14.43537	15268.8
14	3095.238	8.86E+12	283963	4.65E+10	4.31E+11	26.73246	13.13449	14618.48
15	5000	3.16E+12	172176.2	1.58E+10	2.92E+11	32.20333	14.5159	6808.939
16	5000	3.37E+12	175450	1.76E+10	1.63E+11	27.2852	13.2824	6761.054
17	3823.529	5.19E+12	221911.5	2.1E+10	3.27E+11	35.66424	15.3091	8100.814
18	3823.529	6.02E+12	231550	3.8E+10	4.53E+11	24.28757	12.45584	12253.19
19	3823.529	6.01E+12	231500.7	3.8E+10	4.52E+11	24.36554	12.478	12114.14
20	5322.581	4.5E+12	205313.6	2.25E+10	4.15E+11	32.18773	14.51169	8046.974
21	4230.769	7.09E+12	257935.3	3.53E+10	6.53E+11	32.52899	14.59239	11662.51
22	5000	3.25E+12	173646	1.65E+10	2.44E+11	30.10326	14.00552	6774.682
23	3095.238	8.55E+12	281237.8	4.37E+10	6.07E+11	29.41285	13.83318	14763.23
24	3823.529	5.6E+12	227656.1	2.86E+10	3.98E+11	29.44146	13.83988	10384.72
25	2435.897	6.55E+12	250257.3	3.1E+10	8.91E+11	39.55613	16.1423	16352.96
26	3823.529	6.26E+12	232752.8	4.67E+10	5.85E+11	21.78719	11.71173	14306.06
Average	3912.428	5.67E+12	227017	2.94E+10	4.89E+11	31.74342	14.31489	10873.02

Table 10.2 Ratios of Pi Values to Average Pi Values

	π_1/π_{avg}	π_2/π_{avg}	π_3/π_{avg}	π_4/π_{avg}	π_5/π_{avg}	π_6/π_{avg}	π_7/π_{avg}	π_8/π_{avg}
1	0.98	0.97	1.00	1.11	1.59	0.96	0.98	1.17
2	0.98	0.81	0.93	0.59	1.19	1.51	1.24	0.81
3	1.28	0.52	0.74	0.48	0.80	1.22	1.11	0.63
4	0.79	1.35	1.19	1.24	2.07	1.22	1.12	1.44
5	0.98	0.89	0.97	0.82	1.36	1.21	1.11	0.97
6	0.98	0.88	0.96	0.67	0.90	1.23	1.12	0.77
7	0.98	0.94	0.99	0.74	0.50	1.06	1.04	0.75
8	0.98	0.96	0.99	0.93	1.04	1.00	1.00	0.94
9	0.98	1.02	1.01	1.03	0.58	0.85	0.92	0.92
10	0.98	0.94	0.99	0.75	0.50	1.05	1.03	0.75
11	0.98	1.02	1.01	1.21	1.15	0.85	0.92	1.18
12	0.98	1.10	1.02	1.37	0.66	0.70	0.83	1.12
13	0.79	1.46	1.23	1.41	1.57	1.00	1.01	1.40
14	0.79	1.56	1.25	1.58	0.88	0.84	0.92	1.34
15	1.28	0.56	0.76	0.54	0.60	1.01	1.01	0.63
16	1.28	0.59	0.77	0.60	0.33	0.86	0.93	0.62
17	0.98	0.92	0.98	0.72	0.67	1.12	1.07	0.75
18	0.98	1.06	1.02	1.29	0.93	0.77	0.87	1.13
19	0.98	1.06	1.02	1.29	0.92	0.77	0.87	1.11
20	1.36	0.79	0.90	0.76	0.85	1.01	1.01	0.74
21	1.08	1.25	1.14	1.20	1.34	1.02	1.02	1.07
22	1.28	0.57	0.76	0.56	0.50	0.95	0.98	0.62
23	0.79	1.51	1.24	1.49	1.24	0.93	0.97	1.36
24	0.98	0.99	1.00	0.97	0.81	0.93	0.97	0.96
25	0.62	1.16	1.10	1.06	1.82	1.25	1.13	1.50
26	0.98	1.11	1.03	1.59	1.20	0.69	0.82	1.32
Minimum	0.62	0.52	0.74	0.48	0.33	0.69	0.82	0.62
Maximum	1.36	1.56	1.25	1.59	2.07	1.51	1.24	1.50

CHAPTER XI

CONCLUSION

Dimensionless correlations were developed in order to predict the mass flow of refrigerants in adiabatic capillary tubes and in capillary tube/suction line heat exchangers. These dimensionless correlations were regressions of dimensionless parameters generated from the Buckingham Pi Theorem. The geometry factors, condition effects, and fluid properties were the elements used to develop the correlations. Correlations for the mass flow of each refrigerant (R-134a, R-22, and R410a) in adiabatic capillary tubes were generated, as well as, correlations for the mass flow of each refrigerant (R-134a, R-22, R410a, and R600) in capillary tube/suction line heat exchangers. Generalized correlations for both adiabatic capillary tubes and capillary tubes/suction line heat exchangers were also developed. In addition, R-152a was used to verify the correlations, and a correlation simplification process is included in this study.

The specific refrigerant correlations were able to accurately predict the measured mass flow rate. For adiabatic capillary tubes, the deviations ranged from 0.16% to 6.16% for subcooled inlet conditions and from 0.01% to 13.5% for quality inlet conditions. The deviations for capillary tube/suction line heat exchangers ranged from 0% to 8.56%. The average deviations for both adiabatic capillary tubes and capillary tube/suction line heat exchangers are summarized in Table 10.1 for each of four refrigerant types.

Table.11.1 Average Deviations for Specific Refrigerant Correlations

	Adiabatic Capillary Tube		Capillary Tube/Suction Line Heat Exchanger
	Subcooled	Quality	Subcooled
R-134a Correlation	1.65%	6.30%	2.29%
R-22 Correlation	2.51%	3.82%	1.84%
R-410a Correlation	1.75%	4.61%	1.27%
R-600a Correlation			2.95%.

The predicted flow rates from the generalized correlation developed for adiabatic capillary tubes were compared to measured data for R-134a, R-22, and R-410a with subcooled inlet conditions. The deviations varied from 0.04% to 6.32%, with an average deviation of 1.91%. The generalized correlation prediction deviations with quality inlet conditions for R-134a, R-22 and R-410a varied between 0.06% and 21.02% and the average deviation was 4.89%. For capillary tube/suction line heat exchangers, the generalized correlation with subcooled inlet conditions for R-134a, R-22, R-410a, and R-600a yielded deviations from 0.03% to 14.66%, with an the average deviation of 2.47%.The newly developed correlations provide increased prediction accuracy when compared to the correlations in current ASHRAE Reports and ASHRAE Handbooks.

The simplification study showed that increasing the amount of Pi terms above a number of 4 and 5 for adiabatic and diabatic capillary tubes, respectively, did not improve the prediction accuracy.

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APPENDIX A. ADIABAIC CAPILLARY TUBES DATA

Table A.1 R-134a Test Results for Adiabatic Capillary Tubes with Subcooled Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin ℉	Pcapin psia	Pcapout psia	ΔT ℉	Mass Flow Rate lbm/h
2RUN8	25	0.034	130	88.09	174.87	25	30	15.73
2Run13C	25	0.034	130	63.49	124.9	20	30	12.88
CRun13	15	0.026	130	75.19	149.98	28	30	7.1
CRun14	17	0.042	130	74.79	149.91	27	30	26.2
CRun16	25	0.034	130	75.21	150.07	28	30	14.2
CRun23	25	0.034	130	74.61	124.99	29	20	11.37
CRun24	25	0.034	130	82.68	124.99	28	10	10.42
CRun25	25	0.034	130	86.06	150.03	28	20	12.89
CRun26	25	0.034	130	94.95	149.66	26	10	11.79
CRun27	25	0.034	130	83.29	125.01	26	10	10.42
CRun28	25	0.034	130	94.91	175.05	25	20	15.17
CRun29	25	0.034	130	105.87	174.67	28	10	13.34
CRun31	17	0.042	130	85.6	149.79	22	20	23.74
CRun32	17	0.042	130	95.33	149.56	21	10	21.24
CRun33	15	0.026	130	85.02	149.93	29	20	6.58
CRun34	15	0.026	130	94.19	149.88	28	10	6.13
2Run1	25	0.034	130	79.44	125.06	26	14	10.64
2Run3	25	0.034	130	100.69	175.03	28	15	13.88
2Run5	25	0.034	130	100.51	175.04	28	15	13.74
CRun1	19	0.031	165	85.05	150.08	28	20	9.27
CRun4	21	0.039	165	84.47	150.07	27	20	16.97
CRun9	15	0.026	130	88.74	150.08	24	16	6.38
CRun10	17	0.042	130	90.02	149.94	28	15	22.26
CRun18	25	0.034	130	89.97	149.94	28	15	12.68
CRun21	9	0.039	95	73.83	149.96	29	31	25.61
CRun30	25	0.034	130	106.79	199.59	28	18	15.52

Table A.2 R-22 Test Results for Adiabatic Capillary Tubes with Subcooled Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin °F	Pcapin psia	Pcapout psia	ΔT °F	Mass Flow Rate lbm/h
22Run1	31	0.066	60	70.87	209.6	61	30	157.04
22Run2	31	0.066	60	80.42	239.26	66	30	167.87
22Run3	31	0.066	60	82.31	209.79	60	18.5	136.78
22Run4	31	0.066	60	99.67	270.89	72	20	160.55
22Run5	31	0.066	60	93.42	210.35	58	7.5	116.62
22Run6	31	0.066	60	89.47	271.26	71	30	178.52
22Run7	31	0.066	60	91.65	239.69	67	19	148.71
22Run8	31	0.066	60	110.69	270.24	71	9	138.79
22Run9	31	0.066	60	100.72	240.27	62	10	130.8
22Run10	5	0.042	60	79.67	240.77	58	30	52.43
22Run11	5	0.042	60	90.21	240.58	49	20	47.56
22Run12	5	0.042	60	101.09	240.23	47	10	41.14
22Run13	39	0.09	60	80.05	240.42	99	30	360.83
22Run14	39	0.09	60	90.03	240.43	99	20	322.44
22Run15	39	0.09	60	99.97	241.36	98	10	282.67
21Run6A	39	0.09	60	108.33	241.57	90	2	242.58
21Run20A	31	0.066	60	124.76	399.58	69	3	133.57
2CRun1	37	0.078	80	85.63	209.68	73	15	178.78
2CRun2	37	0.078	80	102.12	269.54	97	17	209.89
2CRun3	11	0.054	80	83.62	210.35	46	17	70.58
2CRun5	3	0.054	40	100.38	240.25	55	10	94.62
2CRun6	3	0.054	40	99.3	269.65	59	20	114.61
2CRun8	35	0.078	40	98.87	269.87	100	20	290.5

Table A.3 R-410a Test Results for Adiabatic Capillary Tubes with Subcooled Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin ℉	Pcapin psia	Pcapout psia	ΔT ℉	Mass Flow Rate lbm/h
2BRun1	25	0.034	130	86.34	360.8	68	21	22.44
2BRun2	25	0.034	130	80.3	330	68	20.5	21.25
2BRun3	25	0.034	130	102.64	389.5	68	10.5	20.61
2BRun4	25	0.034	130	76.33	360	65	31	24.24
2BRun5	25	0.034	130	71.51	331	70	29.5	22.98
2BRun6	25	0.034	130	95.74	360	70	11.5	19.77
2BRun7	25	0.034	130	87.23	330.2	65	13.5	19.43
2BRun8	25	0.034	130	92.51	390.8	75	21	23.8
2BRun9	25	0.034	130	81.82	390.9	71	31.5	25.32
2BRun10	17	0.042	130	87.35	359.6	74	20	38.37
2BRun11	17	0.042	130	96.09	361	72	10	34.37
2BRun12	17	0.042	130	75.98	360.1	70	31	41.9
2BRun13	15	0.026	130	77.48	359.1	75	29.5	11.82
2BRun14	15	0.026	130	96.48	359.7	70	10.5	9.8
2BRun15	15	0.026	130	86.26	360	70	21	10.52
CBRun1	21	0.039	165	83.51	360.64	75	23.5	30.18
CBRun2	9	0.039	95	79.27	388.36	75	34	44.59
CBRun4	27	0.034	200	82.09	331.45	74	18.5	16.81

Table A.4 R-152a Test Results for Adiabatic Capillary Tubes with Subcooled Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin °F	Pcapin psia	Pcapout psia	ΔT °F	Mass Flow Rate lbm/h
52Run1	25	0.034	130	91.96	147.64	27	20	10.55
52Run2	25	0.034	130	86.05	135.08	27	20	9.92
52Run3	25	0.034	130	101.04	147.45	26	10	10.21
52Run4	25	0.034	130	96.09	134.81	27	10	9.39
52Run5	25	0.034	130	90.21	122.6	28	9	8.67
52Run6	25	0.034	130	69.72	122.42	28	30	11
52Run7	25	0.034	130	81.54	122.52	28	17.5	9.42
52Run8	25	0.034	130	78.24	135.15	28	27	11.13
52Run9	25	0.034	130	81.2	147.59	28	30	12.25
52Run10	15	0.026	130	85.08	134.97	26	20	5.25
52Run11	15	0.026	130	75.96	135.09	25	30	5.7
52Run12	15	0.026	130	95.33	134.98	28	10	4.82
52Run13	17	0.042	130	93.84	134.97	28	12	17.25
52Run14	17	0.042	130	84.41	134.86	28	21	20.28
52Run15	17	0.042	130	79.16	135.03	28	26.5	20.65
5CRun1	21	0.039	165	86.02	134.87	27	20	13.77
5CRun3	27	0.034	200	78.88	122.48	27	20	7.82
5CRun5	9	0.039	95	75.82	134.84	29	30	20.26
5CRun7	13	0.031	95	84.58	135.14	29	21	10.28
5CRun10	41	0.12	100	65.44	77.33	45	5	206

Table A.5 R-134a Test Results for Adiabatic Capillary Tubes with Quality Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin °F	Pcapin psia	Pcapout psia	Quality X	Mass Flow Rate lbm/h
2RUN2	25	0.034	130	92.34	125.41	26	0.181	4.36
2Run4	25	0.034	130	93.24	124.9	26	0.326	3.48
2Run7	25	0.034	130	114.78	174.75	24	0.141	6.91
2Run10	25	0.034	130	114.81	174.99	23	0.192	6.21
2Run12	25	0.034	130	114.77	174.97	25	0.343	5.34
2Run14	25	0.034	130	92.05	125.05	25	0.189	4.49
CRun8	17	0.042	130	104.2	149.9	24	0.24	8.81
CRun12	15	0.026	130	103.89	149.89	27	0.061	3.95
CRun15	15	0.026	130	104.41	150.42	27	0.331	2.39
CRun17	17	0.042	130	104.13	149.63	27	0.348	7.43
CRun36	25	0.034	130	114.65	174.88	26	0.055	8.09
CRun37	25	0.034	130	104.31	150.22	24	0.295	4.6
CRun38	25	0.034	130	104.27	150.08	24	0.181	5.28
CRun39	25	0.034	130	103.81	149.65	23	0.06	7.16
CRun40	25	0.034	130	92	124.97	24	0.114	4.96
CRun41	15	0.026	130	104.48	150.24	25	0.236	2.52
CRun42	17	0.042	130	104.34	149.86	29	0.138	9.89
CRun3	13	0.031	95	104.28	150.16	26	0.291	4.57
CRun6B	9	0.039	95	104.37	150.14	28	0.129	10.22
CRun6C	9	0.039	95	104.1	149.77	28	0.192	8.93
CRun35	25	0.034	130	104.33	150.03	27	0.605	3.26

Table A.6 R-22 Test Results for Adiabatic Capillary Tubes with Quality Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin °F	Pcapin psia	Pcapout psia	Quality X	Mass Flow Rate lbm/h
23Run1	31	0.066	60	99.51	211.06	59	0.061	80.8
23Run2	5	0.042	60	108.57	240.71	49	0.076	31.04
23Run3	31	0.066	60	117.83	270.15	64	0.085	106.29
23Run4	31	0.066	60	118.05	270.75	65	0.036	112.13
23Run5	31	0.066	60	99.07	210.94	53	0.014	92.19
23Run6	31	0.066	60	99.03	210.15	58	0.038	87.24
23Run7	31	0.066	60	117.84	269.95	67	0.055	109.9
23Run8	5	0.042	60	107.09	239.52	43	0.027	32.78
23Run9	5	0.042	60	108.16	239.41	41	0.08	28.97
23Run10	31	0.066	60	108.45	239.37	61	0.041	99.98
23Run11	31	0.066	60	108.45	238.7	59	0.082	92.23
23Run12	31	0.066	60	108.2	238.75	61	0.003	107.2
23Run13	39	0.09	60	108.35	239.4	94	0.03	220.31
23Run14	39	0.09	60	108.57	239.16	92	0.085	199.53
23Run15	39	0.09	60	108.48	239.32	92	0.065	206.3
2CRun4	11	0.054	80	118.2	271.12	50	0.062	51.13
2CRun7	3	0.054	40	99.06	210.7	50	0.022	63.66
2CRun9	37	0.078	80	98.72	210.82	64	0.05	118.31

Table A.7 R-410a Test Results for Adiabatic Capillary Tubes with Quality Inlets (Wolf et al. 1995)

Run Name	Cap Tube	D_c in.	L_c in.	Tcapin ℉	Pcapin psia	Pcapout psia	Quality X	Mass Flow Rate lbm/h
3BRun1	15	0.026	130	104.85	358.9	70	0.11	6.24
3BRun2	15	0.026	130	104.97	359	62.5	0.241	5.36
3BRun3	15	0.026	130	105.53	360	68	0.36	4.84
3BRun4	17	0.042	130	105.41	361.55	69	0.038	27.34
3BRun5	17	0.042	130	103.23	360.09	70	0.124	23.72
3BRun6	17	0.042	130	105.43	361	70	0.051	25.9
3BRun7	25	0.034	130	98.18	328.36	70	0.039	12.93
3BRun8	25	0.034	130	97.95	327	72	0.113	11.52
3BRun9	25	0.034	130	105.7	361.9	72	0.102	12.96
3BRun10	25	0.034	130	104.86	357.7	71	0.205	11.41
3BRun11	25	0.034	130	105.14	359.4	70	0.052	14.12
3BRun12	25	0.034	130	110.54	387.8	71	0.203	13.16
3BRun13	25	0.034	130	110.57	388	70	0.267	13.37
3BRun14	25	0.034	130	111.45	393.2	70	0.112	14.58
3BRun15	25	0.034	130	98.27	327.64	65	0.199	10.4
CBRun3	13	0.031	95	110.8	389.73	67	0.044	16.81
CBRun5	19	0.031	165	99.27	332	64	0.082	8.4

Table A.8 R-152a Test Results for Adiabatic Capillary Tubes with Quality Inlets (Wolf et al. 1995)

Run Name	Cap Tube	Dc in.	Lc in.	Tcapin ℉	Pcapin psia	Pcapout psia	Quality X	Mass Flow Rate lbm/h
5CRun2	25	0.034	130	97.53	122.63	28	0.046	5.35
5CRun4	25	0.034	130	110.07	147.7	26	0.103	5.58
5CRun6	15	0.026	130	104.42	135.61	28	0.224	2.17
5CRun8	17	0.042	130	103	134.34	28	0.039	9.85
5CRun9	13	0.031	95	97.44	122.69	26	0.117	4.12

APPENDIX B. HEAT EXCHANGERS DATA

Table B.1 R-134a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
4Run1	0.034	155	0.2565	15	60	84.32	8.32	18.30	70.92	149.99	23.51	20.70	13.80	16.83
4Run2	0.034	130	0.2565	15	80	84.34	11.29	14.63	74.61	149.80	25.08	20.60	7.20	19.04
4Run3	0.031	130	0.2565	15	60	84.96	5.66	13.60	71.07	149.95	22.40	20.10	11.20	14.50
4Run4	0.034	130	0.2565	15	40	84.97	8.21	13.48	64.21	149.82	23.42	20.00	9.10	17.72
4Run5	0.034	130	0.3190	15	60	85.75	9.66	18.45	68.32	150.00	24.14	19.30	12.70	18.42
4Run6	0.034	130	0.1940	15	60	84.06	9.16	19.53	73.02	149.77	23.81	20.90	14.40	18.89
4Run7	0.034	130	0.2565	15	20	84.26	6.12	20.68	55.25	150.08	22.45	20.80	18.20	16.65
4Run8	0.034	130	0.2565	15	60	85.30	9.80	17.57	72.36	150.04	24.41	19.80	11.30	19.16
4Run9	0.039	130	0.2565	15	60	84.48	17.59	25.62	70.33	150.21	28.34	20.70	12.60	26.55
4Run10	0.034	180	0.2565	15	60	85.15	6.50	18.53	72.42	150.28	22.42	20.00	16.10	15.70
4Run11	0.034	105	0.2565	15	60	85.06	13.87	17.53	70.01	150.32	26.27	20.10	8.00	21.50
4Run12	0.034	130	0.2565	24	60	84.42	8.53	14.36	70.02	150.11	23.57	20.70	9.70	18.51
4Run13	0.034	80	0.2565	15	60	85.33	14.82	22.32	71.31	150.25	26.79	19.80	11.90	24.28
4Run14	0.034	130	0.2565	6	60	85.18	7.85	17.30	72.37	150.06	23.42	19.90	12.90	18.63
4Run15	0.042	130	0.2565	15	60	85.18	20.98	26.98	70.98	150.28	30.34	20.00	10.90	30.34
4Run16	0.026	130	0.2565	15	60	85.57	3.93	20.25	69.20	150.55	20.25	19.70	22.30	9.12
4Run17	0.034	130	0.2565	15	100	84.73	9.79	15.61	77.71	150.30	24.14	20.44	9.90	19.12
4Run18	0.034	130	0.2565	15	60	84.92	11.46	23.84	70.89	175.31	24.79	29.70	16.90	21.09
4Run19	0.034	130	0.2565	15	60	85.47	7.32	20.83	73.05	125.22	22.94	7.90	17.40	16.10
4Run20	0.034	130	0.2565	15	60	76.49	6.43	16.39	65.16	124.82	22.46	16.70	13.90	16.60

Table B.2 R-134a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	Δ Tsc ℉	Δ Tsh ℉	Mass Flow Rate lbm/h
4Run21	0.034	130	0.2565	15	60	77.31	9.70	16.60	65.07	150.70	24.06	28.00	11.00	18.86
4Run22	0.034	130	0.2565	15	60	94.63	7.99	21.20	78.70	150.89	23.29	10.80	17.10	17.95
4Run23	0.034	130	0.2565	15	60	105.31	10.62	20.46	86.00	175.82	24.62	9.10	13.80	19.71
4Run24	0.034	130	0.2565	15	60	68.85	6.43	18.86	59.94	125.04	22.50	24.40	16.30	16.60
4Run25	0.034	130	0.2565	15	60	84.41	10.15	17.95	69.48	150.48	24.32	20.80	11.90	18.62
4Run26	0.034	130	0.2565	15	60	93.77	11.34	16.93	74.91	176.12	24.84	21.10	9.90	20.64
4Run27	0.026	130	0.2565	15	60	77.69	3.00	12.69	66.79	149.93	21.07	27.30	13.00	9.24
4Run28	0.026	130	0.2565	15	60	94.57	2.57	29.95	80.69	150.09	20.81	10.50	30.80	8.71
4Run29	0.026	130	0.2565	15	60	85.92	2.13	27.13	77.39	150.13	20.92	19.20	27.70	8.83
4Run30	0.042	130	0.2565	15	60	76.23	23.55	27.92	63.85	149.62	32.00	28.70	9.50	31.90
4Run31	0.042	130	0.2565	15	60	95.72	23.15	26.25	77.90	150.24	31.60	9.40	8.40	30.76
4Run32	0.042	130	0.2565	15	60	83.05	23.40	30.83	72.07	149.94	31.88	22.00	12.60	30.89
4Run33	0.034	130	0.2565	15	60	83.99	13.19	25.31	72.03	149.92	26.32	21.00	15.70	18.50
4Run34	0.034	130	0.2565	15	60	83.58	13.71	32.16	72.92	149.91	26.73	21.40	21.80	18.15
4Run35	0.034	130	0.2565	15	60	84.35	16.73	16.55	71.34	149.72	28.60	20.60	3.20	18.83
4Run36	0.034	130	0.2565	15	60	85.70	9.83	12.47	70.40	150.51	24.25	19.60	6.50	18.75
4Run37	0.034	130	0.2565	15	60	84.85	9.05	16.79	71.63	150.36	23.77	20.30	11.80	18.76
4Run38	0.034	130	0.2565	15	60	84.08	10.19	24.48	71.84	150.39	24.25	21.10	18.60	18.57
4Run39	0.034	130	0.2565	15	60	85.98	1.21	14.20	72.97	150.03	19.66	19.10	17.50	18.69
4Run40	0.034	130	0.2565	15	60	84.66	1.78	7.91	70.18	150.15	19.56	20.50	11.40	18.85

Table B.3 R-134a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
4Run41	0.034	130	0.2565	15	60	83.73	3.00	0.63	67.80	150.12	20.40	21.40	2.30	19.18
4Run42	0.034	130	0.3190	15	60	84.82	7.75	23.51	71.31	149.87	23.09	20.20	19.80	17.76
4Run43	0.034	130	0.3190	15	60	83.87	8.89	7.51	66.35	149.81	23.73	21.10	2.60	18.70
4Run44	0.034	130	0.3190	15	60	84.05	9.77	16.34	67.77	149.91	24.26	21.00	10.40	18.49
4Run45	0.034	130	0.1940	15	60	85.21	11.14	17.90	74.23	150.49	24.93	20.00	10.70	18.69
4Run46	0.034	130	0.1940	15	60	84.42	11.50	26.12	74.56	150.23	25.25	20.70	18.40	18.39
4Run47	0.034	130	0.1940	15	60	84.64	13.05	15.91	73.41	150.10	26.26	20.40	6.40	19.21
4Run48	0.034	130	0.2565	15	60	69.89	4.46	18.96	60.77	100.04	21.72	9.20	17.90	13.55
4Run49	0.034	130	0.2565	15	60	97.72	13.52	20.46	79.40	199.70	26.04	23.70	11.30	22.36
4Run50	0.034	155	0.2565	15	60	74.47	2.79	29.02	68.27	125.29	20.79	18.90	29.90	14.18
4Run51	0.034	155	0.2565	15	60	94.89	8.69	22.52	78.57	174.97	23.61	19.60	17.80	18.71
4Run52	0.034	105	0.2565	15	60	72.78	9.18	23.99	62.50	124.71	23.99	20.30	18.50	18.82
4Run53	0.034	105	0.2565	15	60	97.56	13.89	19.55	79.41	175.59	26.32	17.10	9.90	23.04
4Run54	0.034	130	0.2565	15	100	73.88	10.99	20.42	69.49	149.71	24.94	31.00	13.20	20.97
4Run55	0.034	130	0.2565	15	100	94.88	9.07	26.84	86.88	149.66	24.11	10.00	21.20	18.38
4Run56	0.034	130	0.2565	15	20	72.87	7.81	21.21	48.69	149.82	23.27	32.10	17.10	18.29
4Run57	0.034	130	0.2565	15	20	94.62	6.49	26.71	63.93	149.77	22.80	10.30	23.50	16.55
4Run58	0.026	130	0.2565	15	60	87.55	-6.31	18.14	75.72	149.50	16.99	17.30	27.40	9.19
4Run59	0.026	130	0.2565	15	60	87.94	-9.21	23.22	77.80	123.77	15.88	4.70	35.10	7.68
4Run60	0.031	130	0.2565	15	40	74.68	5.73	25.32	63.33	149.64	22.52	30.20	22.70	15.29

Table B.4 R-22 Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	Δ Tsc ℉	Δ Tsh ℉	Mass Flow Rate lbm/h
2Run1	0.034	130	0.2565	15	60	89.16	12.60	37.12	78.75	239.83	47.96	20.50	26.90	22.77
2Run2	0.034	130	0.2565	15	60	97.65	15.34	35.75	82.59	270.51	50.31	21.20	23.00	24.72
2Run3	0.034	130	0.2565	15	60	89.69	17.25	34.84	78.12	269.66	52.37	28.90	20.00	24.99
2Run4	0.034	130	0.2565	15	60	71.42	9.77	36.79	66.10	210.02	45.13	28.30	29.70	20.55
2Run5	0.034	130	0.2565	15	60	89.09	10.72	36.99	77.86	210.22	46.34	10.70	28.50	19.54
2Run6	0.034	130	0.2565	15	60	94.82	13.80	36.90	82.11	238.89	49.05	14.50	25.50	22.00
2Run7	0.034	130	0.2565	15	100	88.58	14.30	30.91	81.93	238.94	49.35	20.70	19.20	23.89
2Run8	0.034	130	0.2565	15	20	89.60	12.66	36.14	66.83	240.56	47.93	20.20	25.90	21.03
2Run9	0.034	80	0.2565	15	60	89.25	21.49	37.63	78.10	240.78	56.39	20.70	18.80	29.09
2Run10	0.034	180	0.2565	15	60	90.38	11.32	37.00	79.33	240.64	46.75	19.50	28.10	19.02
2Run11	0.042	130	0.2565	15	60	89.31	26.98	37.64	75.56	239.85	61.58	20.30	14.00	37.65
2Run12	0.042	130	0.2565	15	60	96.23	27.98	42.14	81.76	240.72	36.02	13.70	17.20	36.61
2Run13	0.026	130	0.2565	15	60	97.83	2.87	46.11	86.22	240.26	39.64	11.90	45.40	10.24
2Run14	0.026	130	0.2565	15	60	88.47	3.92	44.63	82.93	240.06	40.55	21.20	42.80	10.81
2Run15	0.026	130	0.2565	15	60	80.29	5.21	43.72	75.24	240.24	41.54	29.50	40.70	11.10
2Run16	0.034	130	0.1940	15	60	86.22	15.24	22.53	75.63	240.69	49.82	23.70	10.30	23.90
2Run17	0.034	130	0.1940	15	60	85.82	15.53	35.50	76.90	239.82	50.41	23.80	22.70	22.69
2Run18	0.034	130	0.1940	15	60	86.90	15.16	49.37	79.54	241.14	50.10	23.10	36.90	21.86
2Run19	0.034	130	0.3190	15	60	88.55	13.16	49.33	76.69	240.82	47.95	21.40	39.10	21.43
2Run20	0.034	130	0.3190	15	60	88.91	14.20	37.99	76.79	240.77	48.89	21.00	26.80	21.96

Table B.5 R-22 Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	∆Tsc ℉	∆Tsh ℉	Mass Flow Rate lbm/h
2Run21	0.034	130	0.3190	15	60	87.70	16.87	21.22	72.45	240.31	52.00	22.10	6.70	23.30
2Run22	0.034	130	0.2565	24	60	90.61	14.60	37.78	79.57	239.27	49.63	18.80	25.80	22.60
2Run23	0.034	130	0.2565	6	60	90.31	14.53	34.16	78.85	240.73	49.65	19.60	22.10	22.75
2Run24	0.039	130	0.2565	15	60	88.66	39.57	43.29	77.17	241.01	79.99	21.30	5.80	33.07
2Run25	0.031	130	0.2565	15	60	91.58	17.71	41.55	82.51	240.10	53.79	18.10	25.30	16.39
2Run26	0.034	155	0.2565	15	60	91.87	20.42	42.16	82.16	240.14	56.15	17.80	23.60	20.21
2Run27	0.034	105	0.2565	15	60	92.80	23.36	43.24	82.44	240.68	60.57	17.10	20.50	22.87
2Run28	0.034	130	0.2565	15	40	88.96	22.35	42.00	75.98	241.51	58.56	21.20	21.10	22.03
2Run29	0.034	130	0.2565	15	80	89.85	24.28	33.53	82.51	240.74	60.87	20.00	10.50	22.51
2Run30	0.034	130	0.2565	15	60	72.10	18.09	36.61	67.22	179.74	54.10	16.60	20.00	17.08
2Run31	0.034	130	0.2565	15	60	83.91	24.84	26.62	72.18	240.31	61.25	25.90	3.30	23.67
2Run32	0.034	130	0.2565	15	60	90.10	23.97	67.31	83.93	240.58	60.21	19.70	44.90	19.98
2Run33	0.034	130	0.2565	15	60	87.04	34.42	33.78	74.03	240.14	73.27	22.70	0.80	23.38
2Run34	0.034	130	0.2565	15	60	87.54	33.05	46.09	77.92	240.45	71.16	22.30	14.60	22.33
2Run35	0.034	130	0.2565	15	60	101.86	27.69	38.96	87.94	299.90	64.37	25.00	12.90	26.40
2Run36	0.034	130	0.2565	15	60	102.65	28.38	48.26	88.78	269.52	65.13	15.90	21.60	22.97
2Run37	0.034	130	0.2565	15	60	85.60	23.87	38.45	76.30	240.32	60.17	24.20	16.10	22.92
2Run38	0.034	130	0.2565	15	60	82.71	23.76	42.13	75.17	210.03	60.10	17.00	19.80	20.18
2Run39	0.034	130	0.2565	15	60	89.49	26.11	54.96	80.98	239.35	62.73	20.00	30.30	21.31
2Run40	0.034	130	0.2565	15	60	86.60	7.18	10.44	70.79	241.37	42.80	23.50	6.00	24.39
2Run41	0.034	130	0.2565	15	60	86.66	6.97	20.65	72.96	241.20	42.36	23.40	16.70	23.74
2Run42	0.034	130	0.2565	15	60	87.39	6.83	30.46	75.76	239.60	42.74	22.10	26.10	23.02

Table B.6 R-410a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
Brun1	0.034	130	0.2565	15	60	86.54	11.19	30.04	75.5	362.3	76.84	19.6	20.8	25.88
Brun2	0.034	130	0.2565	15	60	93.84	13.34	32.78	80.73	361.7	79.97	12.2	21.5	25.04
Brun3	0.034	130	0.2565	15	60	77.07	11.51	32.68	68.61	363.4	77.33	29.3	23.1	26.7
Brun4	0.034	130	0.2565	15	60	88.86	15.97	34.29	76.6	388	84.23	22.5	20.2	27.23
Brun5	0.034	130	0.2565	15	60	99.36	14.19	34.65	85.54	392	81.44	12.8	22.4	27.21
Brun6	0.034	130	0.2565	15	60	76.87	16.73	33.52	68.82	388.3	85.46	34.6	18.7	28.96
Brun7	0.034	130	0.2565	15	60	78.01	11.41	25.55	67.74	328.9	76.95	20.9	16.3	25.63
Brun8	0.034	130	0.2565	15	60	87.58	13.45	28.4	74.94	326.9	80.48	10.9	16.4	24.41
Brun9	0.034	130	0.2565	15	60	69.23	12.9	24.28	61.45	330.7	79.13	30.1	13.5	26.28
Brun10	0.034	130	0.2565	15	60	70.83	12.56	25.54	61.97	297.5	78.93	20.9	14.9	23.59
Brun11	0.042	130	0.2565	15	60	100.26	31.31	32.85	81.16	359.17	112.2	5.2	3.1	43.4
Brun12	0.042	130	0.2565	15	60	79.33	31.22	38.64	68.5	360.6	112	26.5	9	46.96
Brun13	0.042	130	0.2565	15	60	84.59	33.18	39.75	71.72	355.4	116.1	20.1	8.1	45.2
Brun14	0.026	130	0.2565	15	60	85.61	1.51	37.12	77.32	358.6	62.99	19.8	37.7	13.51
Brun15	0.026	130	0.2565	15	60	95.02	0.73	35.7	83.96	361.6	62.26	11	36.9	13.09
Brun16	0.026	130	0.2565	15	60	77.31	1.72	36.26	71.73	357.7	63.68	27.9	36.4	13.7
Brun17	0.034	130	0.2565	15	60	84.54	12.71	46.65	76.17	360	78.84	21.1	36.1	26.04
Brun18	0.034	130	0.2565	15	60	84.87	16.16	28.02	73.34	362	84.26	21.2	13.9	27.23
Brun19	0.034	130	0.2565	15	60	84.16	18.98	41.3	74.17	358.5	88.84	21.2	24.4	26.47
Brun20	0.034	130	0.2565	15	60	85.4	20.62	54.13	77.48	359.4	91.55	20.1	35.6	25.47
Brun21	0.034	80	0.2565	15	60	81.75	23.59	32.49	69.5	359.4	96.31	23.8	11.1	36.2

Table B.7 R-410a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
Brun22	0.034	180	0.2565	15	60	84.51	10.86	34.76	74.38	358.6	75.68	20.9	26.3	23.59
Brun23	0.034	180	0.2565	15	60	83.88	13.76	36.12	74.06	390.6	80.18	28	24.7	25.48
Brun28	0.034	130	0.194	15	60	85.05	23.7	41.07	77.71	359	96.2	20.4	19.8	27.18
Brun29	0.034	130	0.194	15	60	84.01	27.3	33.75	75	358.29	104.4	21.3	8	27.76
Brun30	0.034	130	0.194	15	60	85.11	29.36	62.71	79.78	360.8	108	20.7	35	25.84
Brun33	0.034	130	0.319	15	60	84.92	23.32	35.79	73.33	363	96.51	21.4	14.3	27.8
Brun34	0.034	130	0.319	15	60	84.12	27.69	49.47	74.32	362.88	105.1	22.2	23.3	27.03
Brun35	0.034	130	0.319	15	60	85.07	27.63	69.27	79.11	359.6	105.2	20.5	43.1	25.25
Brun42	0.034	130	0.2565	15	60	101.7	27.23	38.12	87.13	418.6	104.2	15.5	12.4	29.24
Brun43	0.034	130	0.2565	15	60	86	6.87	29.56	74.7	358	69.78	19.2	25.2	27.9
Brun44	0.034	130	0.2565	15	60	84.45	8.38	22.02	71.34	357.5	71.79	20.7	16.3	28.13
Brun45	0.034	130	0.2565	15	60	84.95	9.16	50.68	75.94	358.8	72.59	20.5	44.4	26.54
Brun50	0.034	130	0.2565	15	60	83.81	37.38	47.51	73.32	360.4	126.1	21.9	11.5	26.59
Brun51	0.034	130	0.2565	15	100	83.53	31.51	44.19	78.94	356.8	113.7	21.5	13.7	28.1
Brun53	0.034	130	0.2565	15	20	85.63	26.71	43.76	63.96	358.1	104.1	19.6	18.1	25.64
Brun56	0.034	130	0.2565	15	80	86.84	21.69	35.82	79.53	359.1	93.93	18.6	15.8	27.68
Brun58	0.034	130	0.2565	15	40	86.87	20.96	33.08	70.14	361	92.86	19	13.7	27.19
Brun63	0.034	130	0.2565	6	60	86.41	23.38	32.43	74.69	360.7	96.62	19.4	10.9	28.32
Brun65	0.034	130	0.2565	24	60	86.34	21.94	38.96	76.93	357.8	94.41	18.9	18.7	26.97
Brun67	0.039	130	0.2565	15	60	85.74	36.27	47.53	75.53	363.1	123.7	20.6	12.5	37.99
Brun68	0.034	105	0.2565	15	60	88.94	30.25	44.96	77.81	359.8	111.1	16.7	15.7	29.46
Brun69	0.031	130	0.2565	15	60	88.2	15.06	43.39	79.45	359.1	82.72	17.3	30.3	20.82
Brun70	0.034	155	0.2565	15	60	87.2	17.37	35.64	76.42	360	86.55	18.5	20.1	24.97

Table B.8 R-600a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	Δ Tsc ℉	Δ Tsh ℉	Mass Flow Rate lbm/h
6run1	0.034	130	0.2565	15	60	85.05	8.84	35	73.93	80.07	13.01	21.6	29.6	8.52
6run2	0.034	130	0.2565	15	60	92.93	15.42	38.58	80.8	80.05	13.98	13.7	29.9	8.23
6run3	0.034	130	0.2565	15	60	74.62	16.22	39.31	70.59	80.74	14.77	32.7	28	8.82
6run4	0.034	130	0.2565	15	60	102.54	15.33	36.55	86.7	90.21	13.77	12.6	28.5	8.57
6run5	0.034	130	0.2565	15	60	81.18	15.66	36.36	73.99	89.83	14.08	33.7	27.3	9.08
6run6	0.034	130	0.2565	15	60	68.18	14.5	37.73	63.94	69.84	13.13	29.1	31.9	7.98
6run7	0.034	130	0.2565	15	60	87.97	14.58	36.92	75.68	69.89	13.25	9.4	30.6	7.42
6run8	0.034	130	0.2565	15	60	79.05	14.93	37.26	71.57	70.28	13.62	18.7	29.7	7.7
6run9	0.034	130	0.2565	15	60	87.6	19.2	37.65	76.65	80.08	17.99	19.1	17	8.06
6run10	0.034	130	0.2565	15	60	87.99	21.11	46.77	78.4	80.16	20	18.8	21.2	7.84
6run11	0.034	130	0.2565	15	60	98.95	18.97	41.65	84.3	99.13	17.47	22.9	22.4	9.61
6run12	0.026	130	0.2565	15	60	94.58	15.39	36.03	81.49	80.09	14.71	12.1	24.9	3.96
6run13	0.026	130	0.2565	15	60	86.38	15.38	43.65	79.47	80.16	14.74	20.4	32.5	3.87
6run14	0.026	130	0.2565	15	60	76.64	16.68	35.85	72.96	80.07	16	30.1	20.8	4.07
6run15	0.042	130	0.2565	15	60	94.26	19.37	36.08	79.63	80.37	16.78	12.7	18.8	13.9
6run16	0.042	130	0.2565	15	60	85.57	20.1	37.52	74.55	80.36	17.43	21.4	18.4	14.75
6run17	0.034	180	0.2565	15	60	87.1	7.23	31.49	75.7	80.98	12.86	20.4	26.6	7.13
6run18	0.034	180	0.2565	15	60	88.05	10.51	35.09	76.57	99.98	13.6	34.4	27.6	8.5
6run19	0.034	80	0.2565	15	60	91.14	15.49	38.49	79.02	79.65	14.79	15.2	27.1	10.36
6run20	0.034	80	0.2565	15	60	94.58	18.61	35.76	80.73	90.11	15.69	20.5	21.6	11.58

Table B.9 R-600a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	Δ Tsc ℉	Δ Tsh ℉	Mass Flow Rate lbm/h
6run21	0.034	130	0.2565	15	60	90.02	1.26	21.38	76.57	79.82	10.7	16.5	24.4	8.12
6run22	0.034	130	0.2565	15	60	88.9	4.7	11.25	72.92	79.89	11.68	17.6	10.6	8.69
6run23	0.034	130	0.2565	15	60	70.02	6.89	36.42	65.4	59.63	12.77	17.1	31.8	6.58
6run24	0.034	130	0.2565	15	60	94.48	13.12	32.32	84	89.81	14.31	20.3	22.5	8.97
6run25	0.034	130	0.2565	15	60	88.68	10.62	55.63	81.17	80.55	13.75	18.4	47.7	7.69
6run26	0.034	130	0.2565	15	60	91.27	30.21	70.68	85.13	80.75	21.36	16	42.1	6.96
6run27	0.034	130	0.2565	15	60	101.84	15.14	34.27	85.63	80.78	15.1	5.5	21.9	8.04
6run28	0.034	130	0.2565	15	60	89.19	7.25	36.66	77.25	89.19	12.53	25.1	32.9	7.97
6run29	0.034	130	0.2565	15	60	101.43	13.88	34.03	86.23	79.91	14.92	5.1	22.3	7.98
6run30	0.034	130	0.2565	15	60	109.81	11.59	36.74	92.17	89.8	13.97	5	28	8.32
6run31	0.034	130	0.2565	15	100	89.21	12.15	35.08	83.52	79.8	14.25	17.3	25.4	8.49
6run32	0.034	130	0.2565	15	20	89.91	9.47	36.87	67.41	80.31	13.71	17	29	7.19
6run33	0.034	130	0.2565	6	60	88.35	10.53	40.31	78.66	80.45	13.96	18.8	31.6	7.89
6run34	0.034	130	0.2565	24	60	88.66	10.97	35.46	77.82	80.43	14.17	18.4	26.1	7.93
6run35	0.034	130	0.2565	15	80	88.09	15.46	37.57	78.85	80.09	15.44	18.6	24.2	8.1
6run36	0.034	105	0.2565	15	60	91.05	14.15	34.81	79.088	80.5	14.96	16	22.9	8.84
6run37	0.034	130	0.194	15	60	88.74	13.8	38.35	78.5	80.39	14.9	18.2	26.7	7.8
6run38	0.034	130	0.194	15	60	88.69	15.93	18.88	75.39	80.49	15.45	18.4	5.5	8.74
6run39	0.034	130	0.194	15	60	89.32	13.48	54.5	81.92	80.52	14.81	17.8	43.1	7.41
6run40	0.034	130	0.319	15	60	86.87	9.34	49.32	76	80.53	13.54	20.2	42.1	7.27

Table B.10 R-600a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
6run41	0.034	130	0.319	15	60	90.49	10.42	37.01	77.77	80.64	13.84	16.7	28.7	7.65
6run42	0.034	130	0.319	15	60	88.32	12.83	20.55	72.16	80.59	14.58	18.8	9.9	8.3
6run43	0.039	130	0.2565	15	60	89.04	18.61	37.2	76.94	80.13	16.2	17.7	21.5	11.16
6run44	0.031	130	0.2565	15	60	90.66	10.11	39.78	80.31	80.63	14.05	16.5	30.8	6.3
6run45	0.034	130	0.2565	15	40	88.73	11.31	41.97	75.4	80.59	14.02	18.4	33.1	7.58
6run46	0.034	155	0.2565	15	60	88.66	15.16	40.19	78.24	80.51	15.18	18.4	27.6	8.62
6run47	0.034	155	0.2565	15	60	88.41	13.91	38.28	76.52	80.51	15.13	18.7	25.9	7.07

Table B.11 R-152a Test Results for Heat Exchangers with Subcooled Inlets (Wolf and Pate 2002)

Run Name	Dc in.	Lc in.	Ds in.	Li in.	Lhx in.	Tcapin ℉	Tcapout °F	Tsuctin ℉	Tsuctout °F	Pcapin psia	Psuctin psia	ΔTsc ℉	ΔTsh ℉	Mass Flow Rate lbm/h
5run1	0.034	130	0.2565	15	60	87.36	15.95	34.31	74.42	135.11	25.42	18.3	22	14.99
5run2	0.034	130	0.2565	15	60	91.81	15.67	31.98	78.51	159.6	25.26	25.3	19.9	15.83
5run3	0.034	130	0.2565	15	60	71.42	12.48	37.87	66.39	109.45	24.19	20.3	27.8	11.67
5run4	0.034	130	0.2565	15	20	87.11	11.48	40.64	66.3	135.09	23.13	18.5	32.6	13.26
5run5	0.026	130	0.2565	15	60	88.22	0.84	49.47	80.44	134.93	18.97	17.3	49.9	6.34
5run6	0.034	80	0.2565	15	60	87.43	21.62	35	75.54	134.96	28.26	18.1	17.7	19.39
5run7	0.042	130	0.2565	15	60	85.47	27.15	32.14	70.61	135.9	31.22	20.6	10.1	24.42
5run8	0.034	130	0.2565	15	100	89.23	14.14	37.46	83.93	136.11	24.7	16.9	26.5	14.41
5run9	0.034	180	0.2565	15	60	87.14	8.52	43.6	79.18	136.36	22.12	19.1	37.5	11.41

APPENDIX C. TABULATED MASS FLOW PREDICTION

Table C.1 R-134a for Adiabatic Capillary Tubes with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
2RUN8	15.73	15.78	16.33	15.74	15.96
2Run13C	12.88	13.03	13.41	12.86	13.92
CRun13	7.1	7.16	7.13	7.13	7.58
CRun14	26.2	25.77	26.59	24.91	26.65
CRun16	14.2	14.64	14.90	14.37	15.28
CRun23	11.37	11.50	12.62	12.03	11.90
CRun24	10.42	10.57	11.20	10.66	10.58
CRun25	12.89	13.08	14.00	13.40	13.18
CRun26	11.79	11.97	12.42	11.83	11.60
CRun27	10.42	10.50	11.21	10.66	10.50
CRun28	15.17	14.81	15.27	14.65	14.57
CRun29	13.34	13.42	13.57	12.92	12.55
CRun31	23.74	23.01	24.98	23.23	22.97
CRun32	21.24	20.92	22.18	20.53	20.03
CRun33	6.58	6.47	6.69	6.65	6.62
CRun34	6.13	5.92	5.95	5.88	5.82
2Run1	10.64	10.93	11.88	11.31	11.11
2Run3	13.88	14.06	14.57	13.92	13.50
2Run5	13.74	14.08	14.56	13.92	13.53
CRun1	9.27	9.13	9.90	9.36	9.35
CRun4	16.97	16.92	18.57	17.02	17.15
CRun9	6.38	6.24	6.45	6.40	6.30
CRun10	22.26	22.06	23.81	22.10	21.64
CRun18	12.68	12.58	13.33	12.73	12.47
CRun21	25.61	25.17	24.62	24.13	25.91
CRun30	15.52	15.95	16.19	15.48	15.07

Table C.2 R-22 for Adiabatic Capillary Tubes with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
22Run1	157.04	153.56	161.29	150.84	151.57
22Run2	167.87	161.46	168.46	162.48	162.06
22Run3	136.78	141.36	145.55	138.17	131.19
22Run4	160.55	157.71	160.84	160.99	152.87
22Run5	116.62	121.41	120.54	117.26	113.91
22Run6	178.52	169.30	175.54	174.09	173.22
22Run7	148.71	149.31	152.89	149.35	141.40
22Run8	138.79	137.48	135.81	138.24	132.96
22Run9	130.8	133.97	133.66	132.69	126.55
22Run10	52.43	50.59	53.12	50.16	50.66
22Run11	47.56	47.14	48.69	46.49	44.43
22Run12	41.14	41.85	42.03	40.80	38.71
22Run13	360.83	359.43	373.25	365.92	368.29
22Run14	322.44	335.13	342.27	339.32	325.48
22Run15	282.67	298.23	296.15	298.90	288.67
2CRun1	178.78	184.22	187.73	178.11	169.07
2CRun2	209.89	206.81	209.19	208.63	198.25
2CRun3	70.58	73.14	75.31	69.97	66.70
2CRun5	94.62	95.89	95.88	96.19	91.53
2CRun6	114.61	112.68	115.20	116.41	109.90
2CRun8	290.5	290.46	295.34	303.99	288.83

Table C.3 R-410a for Adiabatic Capillary Tubes with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
2BRun1	22.44	22.47	24.53	22.50	19.97
2BRun2	21.25	21.58	23.54	21.45	19.00
2BRun3	20.61	20.29	22.49	20.19	18.07
2BRun4	24.24	24.19	26.20	24.37	22.65
2BRun5	22.98	23.16	25.08	23.12	21.41
2BRun6	19.77	20.00	22.10	19.89	17.61
2BRun7	19.43	19.92	21.92	19.74	17.36
2BRun8	23.8	23.21	25.36	23.34	20.70
2BRun9	25.32	25.09	27.20	25.47	23.71
2BRun10	38.37	39.38	43.03	38.59	34.07
2BRun11	34.37	34.54	38.28	33.69	30.49
2BRun12	41.9	42.86	46.42	42.31	39.51
2BRun13	11.82	11.58	12.56	11.97	11.03
2BRun14	9.8	9.51	10.53	9.70	8.64
2BRun15	10.52	10.86	11.86	11.16	9.89
CBRun1	30.18	29.45	32.02	29.27	26.38
CBRun2	44.59	43.23	46.89	43.13	40.44
CBRun4	16.81	16.99	18.52	17.01	15.16

Table C.4 R-152a for Adiabatic Capillary Tubes with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
52Run1	10.55	11.10	11.69
52Run2	9.92	10.58	11.08
52Run3	10.21	9.79	10.34
52Run4	9.39	9.20	9.81
52Run5	8.67	8.67	9.10
52Run6	11	11.53	11.16
52Run7	9.42	9.78	10.21
52Run8	11.13	11.77	11.65
52Run9	12.25	12.81	12.51
52Run10	5.25	5.31	5.50
52Run11	5.7	6.03	5.89
52Run12	4.82	4.61	4.88
52Run13	17.25	16.50	17.59
52Run14	20.28	18.74	19.37
52Run15	20.65	20.17	20.15
5CRun1	13.77	13.47	14.07
5CRun3	7.82	8.24	8.43
5CRun5	20.26	20.21	19.80
5CRun7	10.28	9.88	10.26

Table C.5 R-134a for Adiabatic Capillary Tubes with Quality Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
2RUN2	4.36	4.71	4.87	4.35	4.31
2Run4	3.48	3.92	4.06	3.95	3.94
2Run7	6.91	6.47	6.68	6.46	6.69
2Run10	6.21	5.89	6.08	6.16	6.37
2Run12	5.34	4.93	5.09	5.62	5.79
2Run14	4.49	4.64	4.80	4.31	4.26
CRun8	8.81	8.68	8.96	8.70	8.71
CRun12	3.95	3.64	3.77	3.12	3.20
CRun15	2.39	2.17	2.25	2.39	2.45
CRun17	7.43	7.73	7.99	8.18	8.19
CRun36	8.09	8.66	8.93	7.51	7.79
CRun37	4.6	4.62	4.78	4.88	4.93
CRun38	5.28	5.37	5.55	5.27	5.33
CRun39	7.16	7.52	7.77	6.26	6.35
CRun40	4.96	5.42	5.60	4.67	4.63
CRun41	2.52	2.41	2.49	2.52	2.59
CRun42	9.89	10.29	10.62	9.50	9.55
CRun3	4.57	4.05	4.20	4.74	4.76
CRun6B	10.22	9.65	9.98	9.79	9.77
CRun6C	8.93	8.52	8.82	9.17	9.12
CRun35	3.26	3.70	3.83	4.35	4.38

Table C.6 R-22 for Adiabatic Capillary Tubes with Quality Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
23Run1	80.8	87.97	92.76	79.34	79.49
23Run2	31.04	29.72	31.54	27.39	28.40
23Run3	106.29	100.38	105.91	98.79	102.59
23Run4	112.13	104.64	110.23	113.54	118.40
23Run5	92.19	94.22	99.06	100.15	100.65
23Run6	87.24	89.71	94.50	85.12	85.30
23Run7	109.9	102.40	107.96	105.80	110.09
23Run8	32.78	31.11	32.95	32.05	33.11
23Run9	28.97	29.56	31.37	27.00	27.97
23Run10	99.98	96.65	101.83	96.93	98.83
23Run11	92.23	93.40	98.55	86.57	88.12
23Run12	107.2	109.07	114.34	146.51	150.81
23Run13	220.31	216.46	226.99	227.60	228.98
23Run14	199.53	206.03	216.49	192.72	193.45
23Run15	206.3	208.72	219.21	201.22	202.03
2CRun4	51.13	55.27	58.67	51.16	54.26
2CRun7	63.66	63.72	66.87	72.58	72.50
2CRun9	118.31	122.80	129.65	103.93	103.94

Table C.7 R-410a for Adiabatic Capillary Tubes with Quality Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
3BRun1	6.24	5.89	0.22	6.47	8.35
3BRun2	5.36	5.29	0.20	5.72	7.36
3BRun3	4.84	5.02	0.19	5.39	6.95
3BRun4	27.34	28.19	0.91	26.81	34.05
3BRun5	23.72	23.92	0.78	21.97	27.35
3BRun6	25.9	27.05	0.88	25.55	32.43
3BRun7	12.93	13.97	0.50	13.74	17.22
3BRun8	11.52	12.05	0.43	11.55	14.41
3BRun9	12.96	13.21	0.45	13.28	16.99
3BRun10	11.41	11.91	0.41	11.71	14.91
3BRun11	14.12	14.41	0.50	14.65	18.76
3BRun12	13.16	12.68	0.42	12.95	16.77
3BRun13	13.37	12.22	0.41	12.41	16.05
3BRun14	14.58	13.90	0.46	14.48	18.84
3BRun15	10.4	11.17	0.40	10.58	13.20
CBRun3	16.81	14.65	0.52	16.13	20.88
CBRun5	8.4	8.30	0.29	8.31	10.56

Table C.8 R-152a for Adiabatic Capillary Tubes with Quality Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
5CRun2	5.35	4.21	4.41
5CRun4	5.58	4.51	4.80
5CRun6	2.17	1.82	1.93
5CRun8	9.85	8.22	8.58
5CRun9	4.12	3.53	3.65

Table C.9 R-134a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
4Run1	16.83	16.73	16.97	17.02	10.53
4Run2	19.04	18.89	19.37	19.19	11.88
4Run3	14.50	14.56	14.81	14.72	9.10
4Run4	17.72	17.98	18.17	18.23	11.24
4Run5	18.42	18.50	18.71	18.51	11.39
4Run6	18.89	18.58	18.74	18.51	11.37
4Run7	16.65	17.14	16.95	17.11	10.43
4Run8	19.16	18.50	18.75	18.59	11.44
4Run9	26.55	26.42	26.60	26.29	16.03
4Run10	15.70	15.35	15.58	15.75	9.83
4Run11	21.50	20.93	21.23	20.82	12.71
4Run12	18.51	18.62	18.89	18.77	11.58
4Run13	24.28	24.62	24.61	23.50	14.12
4Run14	18.63	18.59	18.78	18.57	11.44
4Run15	30.34	31.98	32.18	31.82	19.38
4Run16	9.12	9.18	9.31	9.18	5.68
4Run17	19.12	19.35	19.77	19.40	12.01
4Run18	21.09	20.84	20.87	21.10	12.79
4Run19	16.10	15.83	16.05	15.64	9.58
4Run20	16.60	16.42	16.64	16.16	9.92
4Run21	18.86	18.89	19.12	19.15	11.63
4Run22	17.95	18.13	18.26	17.97	11.13
4Run23	19.71	19.73	19.91	20.05	12.43
4Run24	16.60	16.72	16.88	16.48	9.98
4Run25	18.62	18.59	18.81	18.66	11.47
4Run26	20.64	20.57	20.79	20.98	12.98
4Run27	9.24	9.25	9.48	9.53	5.81
4Run28	8.71	8.86	8.97	8.76	5.45
4Run29	8.83	9.12	9.23	9.04	5.59
4Run30	31.90	32.23	32.53	32.58	19.50

Table C.10 R-134a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
4Run31	30.76	30.68	31.15	30.97	18.99
4Run32	30.89	31.89	32.06	31.73	19.17
4Run33	18.50	18.39	18.57	18.38	11.20
4Run34	18.15	18.37	18.47	18.15	11.04
4Run35	18.83	18.18	18.90	18.99	11.82
4Run36	18.75	18.54	18.96	18.90	11.74
4Run37	18.76	18.60	18.82	18.66	11.49
4Run38	18.57	18.60	18.69	18.39	11.26
4Run39	18.69	18.92	18.91	18.51	11.52
4Run40	18.85	19.01	19.12	18.86	11.77
4Run41	19.18	18.95	19.60	19.57	12.51
4Run42	17.76	18.62	18.66	18.30	11.26
4Run43	18.70	18.60	19.28	19.31	12.20
4Run44	18.49	18.55	18.82	18.70	11.50
4Run45	18.69	18.50	18.78	18.65	11.47
4Run46	18.39	18.48	18.60	18.32	11.20
4Run47	19.21	18.38	18.84	18.83	11.62
4Run48	13.55	13.84	14.09	13.43	8.17
4Run49	22.36	22.33	22.47	23.05	14.15
4Run50	14.18	15.00	15.06	14.55	9.01
4Run51	18.71	18.44	18.55	18.75	11.67
4Run52	18.82	18.71	18.78	17.90	10.78
4Run53	23.04	22.98	23.14	22.92	14.08
4Run54	20.97	19.60	19.94	19.76	11.93
4Run55	18.38	18.64	18.87	18.27	11.33
4Run56	18.29	17.39	17.22	17.69	10.53
4Run57	16.55	16.51	16.32	16.37	10.05
4Run58	9.19	9.26	9.32	9.06	5.70
4Run59	7.68	7.74	7.83	7.57	4.71
4Run60	15.29	14.34	14.33	14.37	8.65

Table C.11 R-22 for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
2Run1	22.77	22.23	22.65	22.37	14.75
2Run2	24.72	24.76	24.91	24.29	16.15
2Run3	24.99	25.14	25.40	24.95	16.31
2Run4	20.55	20.52	21.02	21.17	13.57
2Run5	19.54	19.04	19.47	19.89	13.09
2Run6	22.00	21.46	21.94	21.87	14.52
2Run7	23.89	23.35	23.50	23.13	15.47
2Run8	21.03	21.01	21.24	21.17	13.59
2Run9	29.09	28.35	28.73	28.72	18.40
2Run10	19.02	19.05	19.23	19.01	12.73
2Run11	37.65	39.40	39.66	39.21	25.47
2Run12	36.61	37.07	41.59	38.16	26.62
2Run13	10.24	10.39	10.57	10.73	7.21
2Run14	10.81	10.70	11.04	11.06	7.36
2Run15	11.10	11.25	11.30	11.44	7.45
2Run16	23.90	22.88	23.65	23.06	15.40
2Run17	22.69	22.39	22.87	22.69	14.85
2Run18	21.86	21.89	22.53	22.48	14.61
2Run19	21.43	22.85	22.49	22.43	14.60
2Run20	21.96	22.85	22.70	22.53	14.78
2Run21	23.30	23.94	23.72	23.20	15.53
2Run22	22.60	22.04	22.37	22.23	14.65
2Run23	22.75	22.38	22.68	22.44	14.83
2Run24	33.07	32.12	32.40	32.93	21.21
2Run25	16.39	16.94	17.19	17.44	11.43
2Run26	20.21	19.77	20.12	20.32	13.37
2Run27	22.87	23.82	24.31	24.67	15.93
2Run28	22.03	21.45	21.79	22.08	14.19
2Run29	22.51	22.50	23.03	23.05	15.26
2Run30	17.08	17.46	17.64	18.46	11.79

Table C.12 R-22 for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
2Run31	23.67	23.53	24.02	23.69	15.76
2Run32	19.98	20.93	21.44	22.03	14.07
2Run33	23.38	23.38	24.36	23.93	16.26
2Run34	22.33	22.36	21.98	22.76	14.50
2Run35	26.40	26.01	26.88	26.36	17.42
2Run36	22.97	22.96	23.39	23.69	15.48
2Run37	22.92	22.58	22.60	22.89	14.77
2Run38	20.18	19.62	19.65	20.41	13.09
2Run39	21.31	21.58	21.56	22.20	14.18
2Run40	24.39	24.40	24.74	23.45	16.06
2Run41	23.74	23.75	23.84	23.00	15.41
2Run42	23.02	22.86	23.20	22.57	15.01

Table C.13 R-410a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
Brun1	25.88	26.85	27.04	26.96	18.84
Brun2	25.04	25.81	25.94	26.24	18.31
Brun3	26.70	27.29	27.83	27.63	19.13
Brun4	27.23	28.33	28.24	28.32	19.70
Brun5	27.21	27.24	27.09	27.67	19.32
Brun6	28.96	28.91	29.37	29.40	20.14
Brun7	25.63	25.64	26.06	25.59	17.81
Brun8	24.41	24.28	24.66	24.66	17.15
Brun9	26.28	26.41	27.10	26.49	18.24
Brun10	23.59	24.17	24.72	23.91	16.58
Brun11	43.40	43.12	44.17	45.55	31.64
Brun12	46.96	47.08	47.61	47.39	32.61
Brun13	45.20	46.21	46.31	46.07	31.88
Brun14	13.51	13.62	13.53	13.13	9.31
Brun15	13.09	13.08	13.02	12.90	9.14
Brun16	13.70	13.86	13.90	13.44	9.43
Brun17	26.04	26.12	26.38	26.08	18.34
Brun18	27.23	27.51	27.53	27.31	18.99
Brun19	26.47	26.58	26.60	26.39	18.32
Brun20	25.47	26.03	26.03	25.67	17.96
Brun21	36.20	34.55	34.45	34.72	23.57
Brun22	23.59	22.92	23.14	22.64	16.03
Brun23	25.48	24.64	24.80	24.46	17.19
Brun28	27.18	26.82	26.66	26.45	18.29
Brun29	27.76	28.11	27.70	27.14	18.80
Brun30	25.84	26.17	25.89	25.43	17.69

Table C.14 R-410a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
Brun33	27.80	27.54	27.32	27.07	18.71
Brun34	27.03	26.93	26.65	26.36	18.18
Brun35	25.25	25.83	25.62	24.99	17.55
Brun42	29.24	29.75	28.77	29.26	20.28
Brun43	27.90	26.35	26.75	26.65	18.73
Brun44	28.13	27.04	27.38	27.19	19.05
Brun45	26.54	25.76	26.17	25.72	18.30
Brun50	26.59	27.75	27.07	26.58	18.20
Brun51	28.10	27.31	27.46	27.37	18.89
Brun53	25.64	26.83	25.26	24.38	16.64
Brun56	27.68	26.97	27.13	27.14	18.85
Brun58	27.19	27.30	26.62	26.17	18.08
Brun63	28.32	27.64	27.35	27.04	18.75
Brun65	26.97	26.71	26.55	26.39	18.26
Brun67	37.99	38.44	38.06	37.91	26.05
Brun68	29.46	29.47	28.95	29.05	19.86
Brun69	20.82	20.82	20.68	20.43	14.29
Brun70	24.97	24.69	24.64	24.35	17.03

Table C.15 R-600a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
6run1	8.52	8.21	8.08	8.11	4.94
6run2	8.23	7.97	7.92	7.90	4.82
6run3	8.82	8.33	8.23	8.36	4.96
6run4	8.57	8.54	8.64	8.61	5.28
6run5	9.08	8.90	8.94	9.07	5.42
6run6	7.98	7.71	7.33	7.47	4.46
6run7	7.42	7.39	7.06	7.10	4.32
6run8	7.7	7.56	7.29	7.31	4.42
6run9	8.06	8.09	8.29	8.09	4.84
6run10	7.84	7.83	8.14	7.97	4.74
6run11	9.61	9.00	9.57	9.43	5.68
6run12	3.96	3.88	4.05	3.96	2.39
6run13	3.87	3.85	4.06	3.99	2.41
6run14	4.07	4.04	4.23	4.16	2.45
6run15	13.9	14.23	13.87	13.80	8.34
6run16	14.75	14.42	14.16	14.09	8.44
6run17	7.13	7.17	7.26	6.98	4.31
6run18	8.5	8.15	8.58	8.36	5.09
6run19	10.36	9.98	9.53	10.07	6.00
6run20	11.58	10.87	10.70	11.22	6.67
6run21	8.12	8.49	8.13	8.15	5.04
6run22	8.69	8.81	8.62	8.39	5.17
6run23	6.58	6.93	6.43	6.46	3.91
6run24	8.97	8.77	8.91	8.83	5.38
6run25	7.69	7.60	7.79	7.81	4.81
6run26	6.96	7.16	7.74	7.64	4.57
6run27	8.04	8.00	7.81	7.87	4.72
6run28	7.97	8.70	8.73	8.80	5.38
6run29	7.98	7.95	7.71	7.80	4.67
6run30	8.32	8.39	8.27	8.42	5.09

Table C.16 R-600a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 5.1 Prediction	ASHRAE R134a Correlation Prediction	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
6run31	8.49	8.58	8.56	8.30	5.06
6run32	7.19	7.16	7.05	7.43	4.49
6run33	7.89	8.02	8.02	8.01	4.88
6run34	7.93	8.15	8.11	8.07	4.90
6run35	8.1	8.34	8.40	8.20	4.96
6run36	8.84	8.98	8.80	8.95	5.38
6run37	7.8	8.07	8.08	8.04	4.87
6run38	8.74	8.64	9.02	8.45	5.18
6run39	7.41	7.61	7.82	7.81	4.78
6run40	7.27	7.80	7.89	7.92	4.85
6run41	7.65	8.09	8.05	8.03	4.89
6run42	8.3	8.60	8.69	8.38	5.10
6run43	11.16	11.70	11.53	11.47	6.92
6run44	6.3	6.24	6.34	6.29	3.83
6run45	7.58	7.63	7.62	7.77	4.72
6run46	8.62	7.40	7.56	7.36	4.48
6run47	7.07	7.45	7.60	7.39	4.50

Table C.17 R-152a for Heat Exchangers with Subcooled Inlets Mass Flow Prediction

Run Name	Measured Mass Flow Rate, lbm/h	Equation 7.1 Prediction	ASHRAE Generalized Correlation Prediction
5run1	14.99	13.31	8.90
5run2	15.83	15.38	10.24
5run3	11.67	11.44	7.58
5run4	13.26	12.18	8.14
5run5	6.34	6.41	4.42
5run6	19.39	16.96	11.06
5run7	24.42	23.51	15.66
5run8	14.41	13.77	9.25
5run9	11.41	11.25	7.69