UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF REFRIGERANT (R32) FLOW MALDISTRIBUTION MODEL FOR MICROCHANNEL HEAT EXCHANGER

CHNG MING HUI

FK 2016 28

DEVELOPMENT OF REFRIGERANT (R32) FLOW MALDISTRIBUTION MODEL FOR MICROCHANNEL HEAT EXCHANGER

By

CHNG MING HUI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2016

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF REFRIGERANT (R32) FLOW MALDISTRIBUTION MODEL FOR MICROCHANNEL HEAT EXCHANGER

By

CHNG MING HUI

August 2016

Chairman : Associate Professor Tang Sai Hong, PhD
Faculty : Engineering

Conservation of energy becomes a challenging issue in air-conditioning applications. In order to overcome this issue, many researchers have recommended using microchannel heat exchanger and low global warming potential and ozone depletion potential refrigerant, such as R32, in air conditioning systems. However, most of the designers of heat exchanger face a major problem which is the performance deterioration due to tube-side refrigerant maldistribution. It is found that most of the researchers did not quantify the effect of performance deterioration due to refrigerant maldistribution. Besides that, there is no model which is able to investigate the influence of the statistical moments of probability density function on the R32 tube-side flow maldistribution in microchannel heat exchanger. Moreover, there is no researcher developed performance deterioration correlation due to refrigerant tube-side maldistribution. In order to have a comprehensive analysis on tube-side maldistribution in microchannel heat exchangers, it is recommended to quantify the influence of the higher statistical moments of probability density function of the flow maldistribution profiles on the performance degradation. In order to analyze the influence of the higher statistical moments of probability density function of the flow maldistribution profiles on the performance degradation, it is necessary to develop a suitable model which is able to perform the numerical simulation and analyzed refrigerant flow maldistribution. Moreover, a performance deterioration correlation based on refrigerant tube-side maldistribution should be developed in order to reduce the development time of heat exchanger. In order to achieve the goals in this research, a model without sub-cool and superheat and with sub-cool and superheat were developed. Next, the performance degradation of microchannel heat exchanger due to refrigerant tube-side maldistribution was quantified and analyzed. After that, the model considering superheat and sub-cool were validated by doing experiment. Finally, the performance deterioration correlation due to refrigerant maldistribution was being developed. From the numerical simulation, it was found that the performance deterioration factor can up to 1% when the standard deviation was more than 0.3 and the performance deterioration factor can reached 1% for skew below than -0.5. The flow maldistribution profile with high standard deviation and high

negative skew have a large impact on the performance deterioration of microchannel heat exchanger and can up to 10%. Furthermore, the performance deterioration factor reached to 4% when the mean was less than 0.9. It was found that the impact of superheat on performance deterioration factor was only 0.1%. Moreover, it was found that the heat transfer performance of microchannel heat exchanger drops significantly when the sub-cool is very high. In conclusion, a maldistribution profile with low standard deviation, high positive skew, high superheat and low sub-cool was preferred in order to minimize the deterioration effect. Finally, the simple form of the performance deterioration correlation equations was developed to allow a quick calculation of the exchanger thermal performance degradation once the flow maldistribution profile was known. The best possible design of microchannel heat exchanger was able to achieve by extract the statistical moments from simulation. The proposed correlation in this research offers a faster and simpler method to analyze the maldistribution problem.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN KETIDAKSAMAAN PENGALIRAN PENYEJUK (R32) MODEL UNTUK MIKRO PENUKAR HABA

Oleh

CHNG MING HUI

Ogos 2016

Pengerusi : Profesor Madya Tang Sai Hong, PhD
Fakulti : Kejuruteraan

Kebelakangan ini, pemuliharaan sumber tenaga telah menjadi satu isu yang mencabar dalam aplikasi penghawa dingin. Dalam usaha untuk mengatasi isu ini, ramai penyelidik telah mencadangkan menggunakan mikro penukar haba dan R32 dalam sistem penyaman udara. Walau bagaimanapun, pereka cipta penghawa dingin sentiasa menghadapi masalah yang sama, iaitu kemerosotan prestasi mikro penukar haba yang disebabkan oleh ketidaksamaan pengaliran penyejuk. Didapati kebanyakan penyelidik tidak membuat kajian tentang kesan dan kuantiti ketidaksamaan pengaliran penyejuk terhadap kemerosotan prestasi. Selain itu, tidak ada model yang mampu untuk menyiasat kemerosotan prestasi mikro penukar haba yang disebabkan oleh ketidaksamaan pengaliran penyejuk. Lebih-lebih lagi, tidak ada penyelidik mencipta kemerosotan prestasi mikro penukar haba korelasi disebabkan oleh ketidaksamaan pengaliran penyejuk. Dalam usaha untuk mengatasi ketidaksamaan pengaliran penyejuk dalam mikro penukar haba, kita perlu menganalisis kesan seperti sisihan piawai, ukuran kecondongan dan lain-lain lagi terhadap prestasi untuk mikro penukar haba. Ini disebabkan ketidaksamaan pengaliran penyejuk akan merosotkan prestasi untuk mikro penukar haba. Selain itu, hubungan kemerosotan prestasi berdasarkan ketidaksamaan pengaliran penyejuk hendaklah dikaji untuk mengurangkan masa untuk mereka cipta mikro penukar haba. Dalam usaha untuk mencapai matlamat dalam kajian ini, model untuk ketidaksamaan pengaliran penyejuk perlu dicipta. Seterusnya, kemerosotan prestasi mikro penukar haba disebabkan ketidaksamaan pengaliran penyejuk perlu dinilai dan dianalisis. Selepas itu, model tersebut disahkan dengan melakukan eksperimen. Akhir sekali, korelasi kemerosotan prestasi mikro penukar haba disebabkan oleh ketidaksamaan pengaliran penyejuk dicipta. Daripada kajian ini, didapati kemerosotan prestasi mikro penukar haba boleh mencapai 1% apabila sisihan piawai lebih daripada 0.3 dan kemerosotan prestasi mikro penukar haba boleh mencapai 1% apabila ukuran kecondongan kurang daripada -0.5. Didapati aliran profil ketidaksamaan pengaliran penyejuk dengan sisihan piawai yang tinggi dan ukuran kecondongan yang kecil akan memberikan kesan yang besar kepada kemerosotan prestasi mikro penukar haba dan kemerosotan tersebut boleh mencapai 10%.

Kemerosotan prestasi mikro penukar haba boleh mencapai 4% apabila min lebih daripada 0.9. Selain itu, didapati bahawa prestasi pemindahan haba mikro penukar haba menjadi lagi teruk apabila pendinginan lanjut adalah sangat tinggi. Selain itu, didapati bahawa profil ketidaksamaan pengaliran penyejuk dengan sisihan rendah standard, ukuran kecondongan yang tinggi, dan pendinginan lanjut yang rendah dapat menaikkan prestasi mikro penukar haba dari segi pemindahan haba. Pengunaan korelasi kemerosotan prestasi mikro penukar haba disebabkan oleh ketidaksamaan pengaliran penyejuk dapat mencepatkan proses untuk mencipta mikro penukar haba apabila kemerosotan prestasi mikro penukar haba dikira dan diketahui. Reka bentuk terbaik untuk mikro penukar haba dapat dicipta dengan menggunakan korelasi ini. Selain itu, kajian ini menawarkan satu kaedah yang lebih mudah dan cepat dan untuk menganalisis masalah ketidaksamaan pengaliran penyejuk di mikro penukar haba.

ACKNOWLEDGEMENTS

First of all, I would like to take this opportunity to express my deepest appreciation and gratitude to my supervisor, Profesor Madya Dr Tang Sai Hong, Dr. Chin Wai Meng, Profesor Madya Dr. Zulkiflle b. Leman and Professor Madya Dr. Nuraini bt. Abdul Aziz for spending their precious time to explain and assisted me during the whole course of this project. I would like to thank them for giving me valuable suggestions, technical ideas and advice whenever I make mistakes and face difficult problems.

Besides that, I would like to thank to all the staffs of Daikin R&D, for helping me to set up the experiment especially to Mohd. Tarmizi B. Mohd Yusoff, Mazlan bin Saidi, Poh Hong Hong and Yap Woon Kheong.

Nevertheless, I would like to thank to all the staffs of Mechanial and Manufacturing Engineering Department, Faculty of Engineering UPM, for helping and guide me through the whole process of preparation my thesis.

Lastly, I would like to thank to my beloved family. They have giving me confidence, moral and financial support throughout my academic years. To the rest, especially all my course mates; thanks for their sincere support, encouragement and suggestions throughout in completing my thesis.

I certify that a Thesis Examination Committee has met on 30 August 2016 to conduct the final examination of Chng Ming Hui on his thesis entitled " Development of Refrigerant (R32) Flow Maldistribution Model for Microchannel Heat Exchanger" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Shamsuddin bin Sulaiman, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Sapuan bin Salit @ Sinon, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohd Khairol Anuar bin Mohd Ariffin, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

M.S.J. Hashmi, PhD
Professor
Dublin City University
Ireland
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 September 2016

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Tang Sai Hong, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Zulkiflle b. Leman, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Nuraini bt. Abdul Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Chin Wai Meng, PhD
Daikin Research and Development Centre
Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature:____________________ Date:____________________

Name and Matric No.: Chng Ming Hui, GS35962

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to

Signature: ____________________
Name of Chairman of Supervisory Committee: ____________________

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

HVAC	Heating, ventilation and air-conditioner
MCHE	Microchannel heat exchanger
PFC	parallel flow condenser
HFC	Hydroflourocarbon
ODP	Ozone depletion potential
GWP	Global warming potential
CFCs	Chlorofluorocarbons
PDF	Probability density functions
TXV	Thermostatic expansion valve
EXV	Electric expansion valve
CFD	Computational fluid dynamics
TLV-TWA	Threshold limit value–time-weighted average
LFL	Lower flammability limit
MSF	Multistage flash
LHC	Longitudinal heat conduction
TN	Temperature nonuniformity
FN	Flow nonuniformity
NTU	number of transfer unit
PIV	Particle image velocimetry
DRDM	Daikin Research and Development Malaysia
MFM	Mass flow meter
RTD	Resistance temperature detector
BPHE	Braze plate heat exchanger
BBV	Brass ball valve

CHAPTER 1

INTRODUCTION

1.1 Background

Conservation of energy becomes a challenging issue in the 21st century. In order to achieve this target, it is necessary to reduce the power consumption and improve the performance of electrical appliances in term of electrical efficiency. Among all the electrical appliances, heating, ventilation and air-conditioner (HVAC) systems contributes around 50% of total electricity consumption in a building (Luis et al., 2008). The heat exchanger which is the major component of air conditioning system was improved in term of structure, material and etc. in order to enhance the performance of air conditioning system. Among all the heat exchangers, Microchannel heat exchanger (MCHE) offers superior advantages such as compact size, large heat transfer surface area, light weight and low cost. When it is used as a condenser in the air-conditioning unit, it is commonly called as parallel flow condenser (PFC). Besides that, various types of refrigerants have been tested and used as the heat transfer medium in air-conditioning systems to reduce power consumption. Among these, the hydroflourocarbon (HFC) R32 refrigerant is able to meet the requirements as an excellent heat transfer medium which has good thermo-physical properties with zero ozone depletion potential (ODP), low global warming potential (GWP) and high energy efficiency characteristics. However, the MCHE faces a critical challenge of refrigerant flow maldistribution. This is due to the fact that MCHE has many "circuits" as compared to conventional fin-tube heat exchanger. Thus, the refrigerant maldistribution problem in the MCHE must be analyzed in greater detail to arrive at an optimum refrigeration cycle design which gives excellent power savings to the air-conditioner and this statement is also supported by Chin and Raghavan (2011a).

1.2 Microchannel Heat Exchanger

MCHE or PFC was a heat exchanger created at the end of 1980 and it usually consists of flat tubes and folded louvered fins (Copetti et al., 2009). MCHE has a very good promising characteristic which is able to maximize the contact area and increasing the heat transfer performance compared to other traditional heat exchanger (Park & Hrnjak, 2008). Thus, MCHE is widely used as condenser in air conditioner application especially in automobile field. Nowadays, MCHE has been used as condenser in commercial air-conditioning system due to its light weight, low cost, low pressure drop and high efficiency. The use of MCHE in air conditioning system has increasing due to its compact size and good thermal performance (Park & Hrnjak, 2008). Figure 1.1 shows the structure of MCHE. The MCHE has one main entrance and exist. The main entrance let the heat transfer medium such as water or refrigerant to flow into the MCHE. The MCHE has many tubes and each tube tends to its own mass flow rate depends on the distance from its inlet to the main entrance.

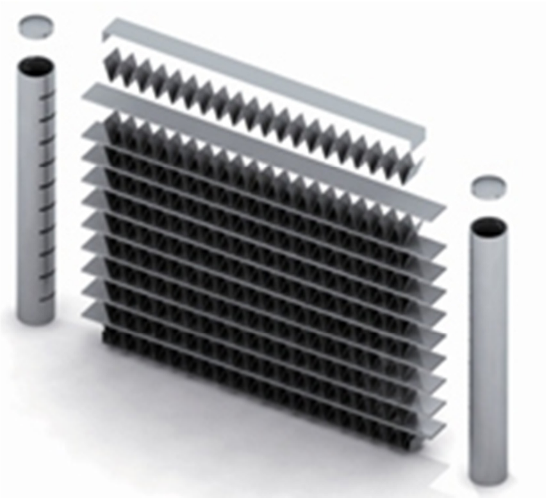

Figure 1.1: Microchannel Heat Exchanger
(Source: SAPA, 2016)

In order to have a comprehensive analysis on the performance of MCHE, the degradation effects due to flow maldistribution on the heat exchanger must be analysed. In previous researches, the effect of maldistribution on fin-tube heat exchanger on the air side had been investigated. It was found that maldistribution will reduce the thermal performance of all range of heat exchanger by 5 – 15% compared to uniform flow distribution (Mueller, 1987). Hydraulic performance deterioration due to the increase of pressure drop could be critical and influence the energy efficiency of the heat exchanger. Besides that, another researcher found that the degradation is mainly affected by the mean and standard deviation of the flow maldistribution profile (Chin & Raghavan, 2011b).

There are many factors which contribute to the occurrence of flow maldistribution such as the design of inlet and outlet headers, number of passes, fin pitch, temperature effects, the design of flow circuits and others. In short, performance deterioration due to flow maldistribution effect is divided into gross maldistribution and passage-to-passage maldistribution (Jiao et al., 2003). Gross maldistribution is uneven distribution effect due to poor design of heat exchanger entrance configuration while passage-to-passage flow maldistribution is mainly caused by manufacturing tolerance.

Besides that, the flow maldistribution problem becomes more severe when heat exchangers are applied in compact designs which involve a tortuous flow path for both the fluid stream (Chin & Raghavan, 2011a). Hence, the effects of maldistribution profile in various kinds of heat exchanger, especially MCHE, should be quantified and analysed in order to design a better heat exchanger. This kind of research is crucial in order to optimize the design of the heat exchanger in air refrigeration system.

1.3 Problem Statement

There were many research works investigated the effect of flow maldistribution in plate-fin and fin-tube heat exchanger. However, there are not much detailed information on the effect of tube-side maldistribution especially in MCHE. Nielsen et al. (2012) found that as the variation of the individual channel thickness of heat exchanger increased, the actual performance of the heat exchanger decreased significantly. Furthermore, Marchitto et al. (2007) indicated that the effects of the operating conditions, the header-channel distribution area ratios and the inlet port orifice plates created a large impact on the pattern of two-phase flow inside the header which caused a large deviation of the flow distribution to the channels. From their research, it is found that most of them just analyze the cause of flow maldistribution in heat exchanger.

Most of the researchers just concluded header, channel design or heat exchanger entrance configuration exerted a significance impact on the performance deterioration but did not analyze and quantify the influence of the higher statistical moments of probability density function of the flow maldistribution profiles on the performance degradation of Heat Exchangers. Wen and Li (2004) indicated that an improved header configuration of plate-fin heat exchanger was able to reduce performance degradation. Besides that, Wen et al. (2006) found that the improved entrance configuration with punched baffle was able to reduce performance deterioration. Chin and Raghavan (2011a) had indicated that any effort to analyse and predict the detrimental effects due to flow maldistribution must take into consideration of the effects of higher statistical moments. Without consideration of those effects, it would be difficult for refrigeration system designers to optimize the performance of the heat exchanger.

Moreover, it is found that most of the models used by previous researchers are not using R32 as heat transfer medium and MCHE. Kaern and Elmegaard (2011) developed a model of a fin-and-tube evaporator with object-oriented modeling language Modelica and use R410A as heat transfer medium. Cho et al. (2010) developed a numerical simulation on the mass flow distribution in microchannel heat sink but the mathematical model is not suitable for air conditioner application. Ranganayakulu et al. (1997), Ranganayakulu et al. (1999) and Wen et al. (2006) developed mathematical model to study flow maldistribution problem in plate-fin heat exchanger. Wiebke et al. (2009) used R134a as heat transfer medium in their mathematical model while Nielsen et al. (2013) used water as heat transfer medium in their mathematical model. Nowadays, the current trend of air conditioning application is moving towards to use lower GWP and ODP refrigerant such as R32. Theoretically, R32 will have higher velocity compared to R410a if their mass flow rate is same. This is due to R32 has smaller density compared to R410a. Thus, flow maldistribution problem will become more significance if R32 is employed as the heat transfer medium in a heat exchanger. MCHE which has the greater performance compared to fin-tube heat exchanger should be employed in flow maldistribution study. Besides that, most of the researchers did not consider the superheat and sub cooling when analyzed flow maldistribution problem in heat exchanger as they were using water as their heat transfer medium. In order to have an actual scenario to simulate the flow maldistribution profiles on the performance degradation of heat exchangers, superheat and sub cooling effect must be analyzed.

To the best knowledge of author, there is no model which is able to describe the influence of the higher statistical moments of probability density function of the refrigerant (R32) flow maldistribution profiles on the performance degradation of Heat Exchangers. Although Chin and Raghavan (2011b) had developed a model which investigated the influence of the higher statistical moments of probability density function of the flow maldistribution profiles on the performance degradation of heat hxchangers, they did not considered the tube-side maldisbution in microchannel heat exchangers. They only analyzed the air side maldistribution in fin tube heat exchanger.

In fact, a model that can precisely describe the real tube-side flow distribution in MCHE has yet remained as a challenging and critical issue in design of heat exchanger. Thus, a suitable model which investigates the influence of the statistical moments of probability density on tube-side refrigerant (R32) flow maldistribution in microchannel heat exchanger is still remaining a challenge.

Besides that, most of the researchers did not develop performance deterioration correlation related to refrigerant maldistribution. The only performance deterioration due to performance deterioration is developed by Chin and Raghavan (2011b). However, they did not consider the tube-side maldisbution in microchannel heat exchangers. In the nutshell, there is none of the researcher develop performance deterioration correlation based on refrigerant tube-side maldistribution.

In summary, the problems are shown as below:

a) Many researchers emphasized on the cause of flow maldistribution in heat exchanger but they did not quantify the refrigerant flow maldistribution.
b) A suitable mathematical model which investigates the influence of the statistical moments of probability density function on refrigerant (R32) tube-side maldistribution in Microchannel Heat Exchanger is still remaining a challenge.
c) There was none of the researcher develop performance deterioration correlation based on refrigerant tube-side maldistribution

It is very important to have a comprehensive analysis on tube-side maldistribution in MCHE so that designer of air conditioner can optimize the performance of heat exchanger by improved the refrigerant flow maldistribution. Hence, the impact of deterioration on the heat exchange performance is reduced and the improved air conditioner is able to save a lot of energy and cost. Besides that, designers is able to save a lot of time when design a heat exchanger without using trial and error method to solve refrigerant flow maldistribution problem. With performance deterioration correlation developed by the author, the designers are able to estimate the performance deterioration of heat exchanger due to refrigerant flow maldistribution within a short period.

1.3 Objectives

This research aims to develop performance deterioration correlation to estimate the performance deterioration of heat exchanger due to tube-side refrigerant flow maldistribution. The objectives of the research are stated as:

a) To develop a model for tube-side refrigerant flow maldistribution in MCHE without sub-cool and superheat effect
b) Quantify the influence of the statistical moments of probability density function of the tube-side refrigerant flow maldistribution profiles on the performance degradation of MCHE without considering sub cooling and superheat effect
c) Improve and generate a model for tube-side flow maldistribution in MCHE which considering sub-cool and superheat effect
d) Analyze the tube-side refrigerant flow maldistribution profiles in term of skew, standard deviation, mean, superheat and sub-cool on the performance degradation of MCHE
e) Set up an experiment which is able to validate the model considering superheat and sub-cool effect

1.4 Scope of the Research

In this work, the fin pattern, number of passes and number of rows remain constant. Moreover, the refrigerant mass flow rate along each tube is assumed constant. The refrigerant mass flow rate is varied from 0.0097kg/s to 0.0414kg/s. The R32 refrigerant inlet temperature is varied from 70°C to 50°C. The fin pattern used in this research is louver. Among of the refrigerant, R32 is employed in this research due to its environment friendly characteristic. The normalized standard deviation is varied from 0.1 to 0.5. Normalized skew is varied from -1 to 1 while normalized mean is varied from 0.9 to 1.2. The superheat of condenser is varied from 4°C to 24°C.

In this study, the effects of tube-side maldistribution will be investigated while air-side distribution is kept uniform. The performance deterioration due to tube-side maldistribution in term of standard deviation, skew and mean is analyzed.

The limitations of this research are:
a) Only applicable to Condenser
b) Air flow distribution is uniform

1.5 Thesis Overview

This thesis describes the analysis of the effect of tube-side flow maldistribution in MCHE. Besides that, the performance deterioration correlation due to refrigerant maldistribution is developed to enhance and speed up the process of designing heat exchanger. Chapter 2 will presents the background and literature review of the effect of maldistribution on heat exchangers. Chapter 3 presents the methodology used to analyse the maldistribution effect and method to develop performance deterioration correlation while Chapter 4 presents the results and discussion. Chapter 5 will presents the summary and recommendation of the research.

REFERENCES

Ablanque, N., Oliet, C., Rigola, J., Pérez-Segarra, C., & Oliva, A. (2010). Two-phase flow distribution in multiple parallel tubes. *International Journal of Thermal Sciences,* 49(6): 909–921.

Ahmad, M., Berthoud, G., & Mercier, P. (2009). General characteristics of two-phase flow distribution in a compact heat exchanger. *International Journal of Heat and Mass Transfer,* 52: 442–450.

ASHRAE. (1978). *ASHRAE standard, methods of testing forced circulation air cooling and air heating coils*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

ASHRAE. (2008). *ASHRAE Standard, Number Designation and Safety Classification of Refrigerants*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers

ASHRAE. (2013). ASHRAE handbook: Fundamentals. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers

Bolaji, B., O., & Huan, Z. (2013). Ozone depletion and global warming: Case for the use of natural refrigerant – a review. *Renewable and Sustainable Energy Reviews,* 18: 49–54.

Byun, H. W., & Kim, N. H. (2011). Refrigerant distribution in a parallel flow heat exchanger having vertical headers and heated horizontal tubes. *Experiment Thermal and Fluid Science,* 35: 920-930.

Cao, X., Li, Z. Y., Shao, L. L., & Zhang, C. L. (2016). Refrigerant flow through electronic expansion valve: Experiment and neural network modeling. *Applied Thermal Engineering,* 92: 210–218.

Chang, Y. J. and Wang, C. C. 1997. A generalized heat transfer correlation for louver fin geometry, *International Journal of Heat and Mass Transfer*, 40: 533-544.

Chin, W. M., & Raghavan, V. R. (2011a). On the Adverse Influence of Higher Statistical Moments of Flow Maldistribution on the Performance of a Heat Exchanger. *International Journal of Thermal Sciences*, 50: 581-591.

Chin, W. M., & Raghavan, V. R. (2011b). The influence of the moments of probability density function for flow maldistribution on the thermal performance of a fin-tube heat exchanger. *International Journal of Thermal Sciences*, 50: 1942-1953.

Chiou, J. P. (1978). Thermal Performance Deterioration in Crossflow Heat Exchanger due to Flow Nonuniformity. *Journal of Heat Transfer*, 100: 580-587.

Choi, J.M., Payne, W.V., & Domanski, P.A. (2003). Proceedings from International Congress of Refrigeration: *Effects of nonuniform refrigerant and air flow distribution of finned-tube evaporator performance.* Washington, DC: USA.

Chwalowski, M., Didion, D.A., & Domanski, P.A. (1989). Verification of evaporator computer models and analysis of performance of an evaporator coil. *ASHRAE Transactions*, 95(1): 793–802.

Chisholm (1983). *Two-Phase Flow in Pipelines and Heat Exchangers.* New York: Longman.

Chisholm, D. (1973). Pressure gradients due to friction during the flow of evaporation two-phase mixtures in smooth tubes and channels. *International Journal of Heat and Mass Transfer*, 16: 347–358.

Churchill, S. W. (1977). Frictional equation spans all fluid flow regimes. *International Journal of Chemical Engineering,* 84: 91-92.

Cho, H. & Cho, K. (2007). Performance comparison of microchannel evaporators with refrigerant R-22. *Journal of Mechanical Science and Technology,* 21: 1926-1934.

Cho, E. S., Choi, J. W., Yoon, J. S. & Kim, M. S. (2010). Modeling and simulation on the mass flow distribution in microchannel heat sinks with non-uniform heat flux conditions. *International Journal of Heat and Mass Transfer,* 53: 1341-1348.

Collier, J. G., & Thome, J. R. (1994). *Convective Boiling and Condensation*. Oxford: Oxford University Press.

Copetti, J. B., Macagnan, M. H., & Figueiredo, C.O. (2009). Proceedings from seventh international conference on Enhanced, Compact and Ultra-Compact Heat Exchanger: *Design and Optimization of Minichannel Parallel Flow Condensers.* UNISINOS Sao Leopoldo, RS: Brazil.

Danga, T., & Teng, J. (2011). The effects of configurations on the performance of microchannel counter-flow heat exchangers–An experimental study. *Applied Thermal Engineering,* 31: 3946–3955.

DataFit, Version 9.0. (2010). Oakdale Engineering, Oakdale, Pennsylvania, USA, 2010. Retrieved from http://oakaleengr.com.

David, J., Timoney, & Patrick, J. F. (1994). Some effects of air flow maldistribution on performance of a compact evaporator with R134a. *Heat Recovery Systems*, 14: 517-523.

Domanski, P. A. (1991). Simulation of an Evaporator with Non-Uniform One-Dimensional Air Distribution. *ASHRAE Trans.actions*, 97(1): 793-802.

Dossat, R. J. (1961). *Principle of refrigeration.* New York and London: John Willey & Sons.

Dossat, R. J. (1997). *Principle of refrigeration (4th Edition).* Upper Saddle River: Prentice Hall.

Fagan, T. J. (1980). The effects of air flow mal-distributions on air-to-refrigerant heat exchanger performance, *ASHRAE Transactions*, 86(2): 699-713.

Fettaka, S., Thibault, J., & Gupta, Y. (2013). Design of shell-and-tube heat exchangers using multiobjective optimization. *International Journal of Heat and Mass Transfer*, 60: 343–354.

Gnielinski, V. (1976). New equations for heat and mass transfer in turbulent pipe and channel flow. *International Chemical Engineering,* 16: 359-368.

Hermes, C. J. L. (2013). Thermodynamic design of condensers and evaporators: Formulation and applications. *International Journal of Refrigeration*, 36:633-640.

Huber, D. & Walter, H. (2010). Proceedings from International conference on theoretical and applied mechanics: *Forced convection heat transfer in the transition region between laminar and turbulent flow for a vertical circular tube*. USA.

ISO 5151. (2010). *Non-ducted air conditioners and heat pumps – Testing and rating for performance.* Geneva, Switzerland: ISO/IEC.

Jiang, H., Aute, V., and Radermacher, R. (2006). Coil Designer: a general-purpose simulation and design tool for air-to-refrigerant heat exchangers. *International Journal of Refrigeration*, 29: 601–610.

Jiao, A. J., Zhang, R., & Jeong, S. (2003). Experimental Investigation of Header Configuration on Flow Maldistribution in Plate-Fin Heat Exchanger. *Applied Thermal Engineering,* 23: 1235-1246.

Kamiaka, T., Dang, C., & Hihara, E. (2013). Vapor-liquid equilibrium measurements for binary mixtures of R1234yf with R32, R125, and R134a. *International Journal of Refrigeration*, 36: 965-971.

Karagoz, S., Yilmaz, M., Comakli, O., & Ozyurt, O. (2004). R134a and various mixtures of R22/R134a as an alternative to R22 in vapour compression heat pumps. *Energy Conversion and Management,* 45: 181–196.

Kim, M. H. & Bullard, C. W. (2002). Performance evaluation of a window room air conditioner with microchannel condensers. *Journal of Energy Resources Technology*, 124(1): 47-55.

Kim, J.H. & Groll, E. A. (2003). Proceedings from ASHRAE Transactions Technical and Symposium Papers: *Performance comparisons of a unitary split system using microchannel and fin-tube outdoor coils*. Kansas City, MO: United States.

Kaern, M. R., & Elmegaard, B. (2011). *Analysis of refrigerant mal-distribution in fin-and-tube evaporators.* (Unpublished doctoral dissertation). Technical University of Denmark, Denmark.

Koern, M. R., Brix, W., Elmegaard, B., & Larsen, L. F. S. (2011). Compensation of Flow Maldistribution in Fin-and-tube Evaporators for Residential Air-conditioning. *International Journal of Refrigerant.* 34: 1230-1237.

Kondo, F., & Aoki, Y. (1986). Prediction method on effect of thermal performance of heat exchanger due to non-uniform air flow distribution. SAE Transactions doi:10.4271/850041.

Kumar S., & Rajagopal, K. (2007). Computational and experimental investigation of low ODP and low GWP HCFC-123 and HC-290 refrigerant mixture alternate to CFC-12K. *Energy Conversion and Management*, 48: 3053–3062.

Kew, P. A. & Reay, D, A. (2011). *Compact/Micro-Heat Exchangers - Their Role in Heat Pumping Equipment.* Applied Thermal Engineering, 31: 594-601.

Lalot, S., Florent, P., Lang, S. K., & Bergles, A. E. (1999). Flow Maldistribution in Heat Exchangers. *Applied Thermal Engineering*, 19: 847-863.

Lee, J., & Domanski, P. A. (1997). Impact of Air and Refrigerant Maldistributions on the Performance of Finned-Tube, *Report DOE/CE/23810-81* for ARI, National Institute of Standards and Technology, Gaithersburg, MD.

Lee, J., Kwon, Y. C., & Kim, M. H. (2003). An Improved Method for Analyzing a Fin and Tube Evaporator Containing a Zeotropic Mixture Refrigerant with Air Maldistribution *International Journal of Refrigerant.* 60: 707 – 720.

Lee, H. J. & Lee, S. Y. (2001). Heat transfer correlation for boiling flows in small rectangular horizontal channels with low aspect ratios. *International Journal of Multiphase Flow,* 27: 2043–2062.

Lemmon E. W. (2004). *NIST reference fluid thermodynamic and transport properties database (REFPROP), Version 6.0 User Manual,* National Institute of Standards and Technology (NIST) Standard Reference Database 23.

Li, J., Wang, S. F., & Zhang, W. J. (2011). Air-side Thermal Hydraulic Performance of An Integrated Fin and Micro-channel Heat Exchanger. *Energy Conversion and Management,* 52: 983–989.

Li, Q., Flamantb, G., Yuana, X., Neveub, P, & Luod, L. (2011). Compact Heat Exchangers: A Review and Future Applications for A New Generation of High Temperature Solar Receivers. *Renewable and Sustainable Energy Reviews*, 15: 4855– 4875.

Li, Z. Z. (2009). Flow Maldistribution and Thermal Performance Deterioration in a Cross-Flow Air to Air Heat Exchanger with Plate-Fin Cores. *International Journal of Heat and Mass Transfer*, 52: 4500-4509.

Lockhart, R. W., & Martinelli, R. C. (1949). Proposed correlation of data for isothermal two-phase, two-component flow in pipes. *Chemical Engineering Prog*ress, 45: 39–48.

Luis, P., Jose, O., & Christine, P. (2008). A Review on Buildings Energy Consumption Information. *Energy and Buildings*, 40: 394-398.

Marchitto, A., Devia, F., Fossa, M., Guglielmini, G., & Schenone, C. (2007). Experiments on Two-Phase Flow Distribution inside Parallel Channels of Compact Heat Exchangers. *International Journal of Multiphase Flow*, 34: 128-144.

Martinelle, R. C., & Nelsom. D. B. (1948). Prediction of pressure drop during forced-circulation boiling of water. *ASME Transaction*, 70: 695–702.

Martinez, I. (1992). Heat Exchanger. Retrieved from http://webserver.dmt.upm.es/~isidoro/bk3/c12/Heat%20exchangers.pdf

Mathew, B., & Hegab, H. (2010). Application of Effectiveness- NTU Relationship to Parallel Flow Microchannel Heat Exchangers Subjected to External Heat Transfer. *International Journal of Thermal Sciences*, 49: 76-85.

Microsoft Excel (2010). Microsoft, USA. 2010. Retrieved from https://products.office.com/en-us/excel.

Minton, P. E. (1986) *Handbook of evaporation technology.* Westwood, USA: Noyes Publicatios.

Mishima, K. & Hibiki, T. 1996. Some characteristics of air–water two-phase flow in small diameter vertical tubes. *Int. J. Multiphase Flow,* 22: 703–712.

Mondt, J. R. (1977). Effects of nonuniform passages on deepfold heat exchanger performance. *Journal of Engineering for Power,* 99: 657-663.

Mott, R. L. (2005). *Applied fluid mechanics (6th Edition).* Upper Saddle River: Prentice Hall.

Mueller, A. C. (1987). Effets of Some Types of Maldistribution on the Performance of Heat Exchanger. *Heat Tramsfer Engineering*, 8(2): 75-86.

Munish, G. (2010). *Numerical Study of Heat Transfer Enhancement in a Plate-fin Heat Exchanger using Rectangular Winglet Type Vortex Generator.* (Unpublished doctoral dissertation). National Institute of Technology, Kurukshetra, India.

Nielsen, K. K., Engelbrecht, K., Christensen, D. V., Jensen, J. B., Smith, A., & Bahl C. R. H. (2012). Degradation of the Performance of Microchannel Heat Exchangers due to Flow Maldistribution. *Applied Thermal Engineering*, 40: 236-247.

Nielsen, K. K., Engelbrecht, K., & Bahl, C. R. H. (2013). The influence of flow maldistribution on the performance of inhomogeneous parallel plate heat exchangers. *International Journal of Heat and Mass Transfer*, 60: 432–439.

Nordborg. (2007). *Refrigeration - an introduction to the basics.* Retrieved from http://www.danfoss.com/nr/rdonlyres/f35695fe-f4a2-40b9-847f-e81e20a5eea8/0/pf000f202.pdf

SAPA. (2016). *Manifolds.* Retrieved from http://www.sapagroup.com/en/precision-tubing/hvacr/products/manifolds/

Oh, S. K., Ko, C. S., Lang, D. Y., Sa, Y. C., Oh, S. Y., & Chung, B. Y. (2003). An experimental study on the wet performance of flat tube heat exchangers. Proceedings of the SAREK 2003, Summer Annual Conference: 262-267.

Park, C. Y., & Hrnjak, P. S. (2008). Experimental and Numerical Study on Microchannel and Round-Tube Condensers in a R410A Residential Air-Conditioning System. *International Journal of Refrigeration*, 31(5): 822-831.

Qu, W., & Mudawar, I. (2003). Measurement and prediction of pressure drop in two-phase micro-channel heat sinks. *International Journal of Heat and Mass Transfer,* 46: 2737–2753.

Rabas, T. J. (1985). The effect of tubeside maldistribution on the thermal performance of condensers used in multistage flash distillation plants. *Desalination,* 55: 515-528.

Ranganayakulu, C. H., Seetharamu, K. N., & Sreevatsan K. V. (1987). The effects of inlet fluid flow non-uniformity on thermal performance and pressure drops in cross-flow plate-fin compact heat exchangers. *International Journal of Heat and Mass Transfer,* 40(1): 27-38.

Ranganayakulu, C. H., Seetharamu, K. N., & Sreevatsan K. V. (1997). The effects of inlet fluid flow nonuniformity on thermal performance and pressure drops in crossflow plate-fin compact heat exchangers. *International Journal of Heat and Mass Transfer,* 40: 27-38.

Ranganayakulu, C. H., & Seetharamu, K. N. (1999). The combine effects of longitudinal heat conduction, flow nonuniformity and temperature nonuniformity in crossflow plate-fin heat exchangers. *International Journal of Heat and Mass Transfer,* 26: 669-678.

Robert, M. (2007). *Fundamentals of HVAC Systems (1st Ed.).* UK: Elsevier.

Ryu, K., & Lee, K. S. (2015). Generalized heat-transfer and fluid-flow correlations for corrugated louvered fins. *International Journal of Heat and Mass Transfer,* 83: 604–612.

Shah, M. M. (1979). A general correlation for heat transfer during film condensation inside pipes. *International Journal of Heat and Mass Transfer,* 22: 547-556.

Shah, M. M. (2013). *General Correlation for Heat Transfer During Condensation in Plain Tubes: Further Development and Verification.* Paper presented at the meeting of the ASHRAE Annual Conference 2013, Denver. July 2013.

Shah, R. K. & London, A. L. (1980). Effects of nonuniform passages on compact heat exchanger performance. *Journal of Engineering for Power*, 102: 653-659.

Shah, R. K., & Sekulic, D. P. (1981). *Classification of heat exchangers, in Heat Exchangers: Thermal-Hydraulic Fundamentals and Design.* Washington, DC: Hemisphere Publishing.

Shah, R. K., & Sekulic, D. P. (2003). *Fundamentals of heat exchanger design.* Hoboken, USA: John Willey & Sons.

Shah, R. K., & Sekulić, D. P. (2007). *Classification of Heat Exchangers, in Fundamentals of Heat Exchanger Design*. Hoboken, NJ, USA: John Wiley & Sons.

Shah, R. K., & Webb, R. L. (1983). *Heat Exchangers: Theory and Practice*. Washington, DC: Hemisphere/McGraw-Hill.

Sheskin, D. J. (2007). *Handbook of Parametric and Nonparametric Statistical Procedures*, fourth ed. Boca Raton: Chapman & Hall/CRC.

Singh, P., Lal, H., & Ubhi, B. S. (2014). Design and analysis for heat transfer through fin with extensions. *International Journal of Innovative Research in Science, Engineering and Technology,* 3: 12054-12061

Stockburger, D. W. (1996). *Statistics.* Retrieved from http://www.psychstat.missouristate.edu/introbook/sbk13m.htm

Subramaniam, V. (2004) Design of air-cooled microchannel condensers for mal-distributed air flow conditions. (Master's thesis). Georgia Institute of Technology. Retrieved from http://hdl.handle.net/1853/5088.

Tran, T. N., Chyu, M. C., Wambsganss, M. W., & France, D. M. (2000). Two-phase pressure drop of refrigerants during flow boiling in small channels: an experimental investigation and correlation development. *International Journal of Multiphase Flow,* 26: 1739–1754.

Villanueva, H. H. S., & Mello, P. E. B. (2015). Heat transfer and pressure drop correlations for finned plate ceramic heat exchangers. *Energy,* 88: 118-125.

Vist, S., & Pettersen, J. (2004). Two-phase flow distribution in compact heat exchanger manifolds. *Experimental Thermal and Fluid Science,* 28: 209–215.

Wang S. K. (2000). *Handbook of air conditioning and refrigeration (2nd Ed.).* New York: McGraw-Hill.

Wen, J. & Li, Y. (2004). Study on Flow Distribution and Its Improvement on the Header of Plate-Fin Heat Exchanger. *Cryogenics*, 44: 823-831.

Wen, J., Li, Y., Zhou, A., Zhang, K., & Wang, J. (2006). PIV Experimental Investigation of Entrance Configuration on Flow Maldistribution in Plate-Fin Heat Exchanger. *Cryogenics*: 46, 37-48.

Wiebke, B., Martin, R. K., & Brian, E. (2009). Modelling refrigerant distribution in microchannel evaporators. *International Journal of Refrigeration,* 32: 1736-1743.

Xu, X., Hwang, Y. H., & Radermacher, R. (2013). Performance Comparison of R410A and R32 in Vapor Injection Cycles. *International Journal of Refrigeration*, 36: 892-903.

Yang. C. Y. & Lin, T. Y. (2007). Heat transfer characteristics of water flow in microtubes. *Experimental Thermal and Fluid Science,* 32: 432–439.

Yang, C. Y., Chen, C. W., Lin, T. Y., & Kandlikar, S. G. (2012). Heat transfer and friction characteristics of air flow in microtubes. *Experimental Thermal and Fluid Science,* 37: 12–18.

Yu, W., France, D. M., Wambsganss, M. W., & Hull, J. R. (2002). Two phase pressure drop, boiling heat transfer, and critical heat flux to water in a small-diameter horizontal tube. *International Journal of Multiphase Flow,* 28: 927–941.

Zhao, Y., Liang, Y., Sun, Y., & Chen, J. (2012). Development of a mini-channel evaporator model using R1234yf as working fluid. *International Journal of Refrigeration*, 35: 2166-2178.

Zou, Y., Tuo, H., & Hrnjak, P. S. (2014). Modeling refrigerant maldistribution in microchannel heat exchangers with vertical headers based on experimentally developed distribution results. *Applied Thermal Engineering*, 64: 172-181.