UNIVERSITI TEKNIKAL MALAYSIA MELAKA

STUDY ON PERFORMANCE OF COMPACT FINNED HEAT EXCHANGER USING OPEN-CELL COPPER FOAM

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Faculty Of Mechanical And Manufacturing Engineering Technology

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MOHAN RAJ A/L BASKARAN

A thesis submitted in fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering Technology (Refrigeration and Air-Conditioning Systems) with Honours

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2022

DECLARATION

I Declare That This Report Entitled "Study On Performance Of Compact Finned Heat Exchanger Using Open-Cell Copper Foam" Is The Result Of My Own Research Except As Cited In The References.The Project Report Has Not Been Accepted For Any Degree And Is Not Concurrently Submitted In Candidature Of Any Other Degree.

Signature : MOHAN RAJ

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Name : Mohan Raj A/L Baskaran

Date : 18 January 2022

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APPROVAL

I Hereby Declare That I Have Checked This Project Report And In My Opinion, This Report Is Adequate In Terms Of Scope And Quality For The Award Of The Bachelor Of Mechanical Engineering Technology (Refrigeration And Air-Conditioning Systems) With Honours.

Signature : DR. SETYAMARTANA PARMAN

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Supervisor Name : Dr. Setyamartana Parman

Date : 18 January 2022

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DEDICATION

I would like to dedicate this report for both my parents Baskaran A/L Raju and Parimala A/P Thenamoorthy as they are my lovable courage, inspiration, dedication and strength to complete my project until the end. I also would like to thank to my sisters and friends as they too have helped me in term of financial and motivation during my years of study. Furthermore, I also would like to tell my thanks to my classmates who always supports and updates on the latest updates on the projects.

ABSTRACT

Heat exchangers are widely applied in different fields that can range from heavy industries to small electronic devices. The need for an increase in the effectiveness is of great concern for heat exchanger manufactures to produce better heat exchanger devices. The use of open-cell metal foam in manufacturing heat exchangers is one of the many methods being studied at the moment due to its unique structural and thermal properties. The aim of this thesis is to carry out experimental analysis of the performance of the compact heat exchanger based on open-cell copper foam. To facilitate in this process of performance analysis, an in-house small scale wind tunnel using air as coolant is developed as the test rig. The experiments were conducted on copper foam with porosity, ε of 0.93 and 60 PPI (pores per inch). Different configurations of the compact finned copper foam heat exchanger were tested at varying Reynolds number. The performance of the completed heat exchanger test rig was judged by studying the flow uniformity in the test section area and was found to be satisfactory. The thermal performance of configuration 1 was 2.5 to 5 times better for fixed flow condition and 1.2 to 2.5 times better for fixed pumping power condition as it has twice the heat exchange area than configuration 2. But the pressure drop for configuration 2 was 5 times lower due to the reduced flow resistance courtesy of the air gap in between the finned copper foam. It is recommended that further variation in the configuration is studied in order to further increase the effectiveness of the compact finned metal foam heat exchanger.

ABSTRAK

Penukar haba digunakan secara meluas dalam bidang yang berbeza dan terdiri daripada industri berat ke peranti elektronik kecil. Keperluan untuk meningkatkan keberkesanan adalah kebimbangan yang besar untuk pengilang penukar haba untuk menghasilkan alat penukar haba yang lebih baik. Penggunaan busa logam sel terbuka dalam pembuatan penukar haba adalah salah satu daripada banyak kaedah yang sedang dikaji pada masa ini disebabkan oleh sifat-sifat struktural dan haba yang uniknya. Tujuan tesis ini adalah untuk menjalankan analisis eksperimen untuk prestasi penukar haba padat berdasarkan busa tembaga sel terbuka. Untuk memudahkan dalam proses analisis prestasi ini, sebuah terowong angin kecil dalaman menggunakan udara sebagai penyejuk dibangunkan sebagai pelantar ujian. Eksperimen dilakukan pada busa tembaga dengan porositas, ε 0.93 dan 60 PPI (liang per inci). Penukar haba busa tembaga padat bersirip yang berbeza konfigurasi diuji pada nombor Reynolds yang berbeza-beza. Prestasi rig ujian penukar haba telah dikaji untuk keseragaman alir di kawasan ujian dan didapati memuaskan. Prestasi terma konfigurasi 1 adalah 2.5 hingga 5 kali lebih baik untuk keadaan aliran tetap dan 1.2 hingga 2.5 kali lebih baik untuk keadaan kuasa pam yang tetap kerana ia mempunyai dua kali kawasan pertukaran haba daripada konfigurasi 2. Tetapi penurunan tekanan untuk konfigurasi 2 adalah 5 kali lebih rendah kerana rintangan aliran dikurangkan oleh jurang udara di antara sirip busa tembaga. Adalah disyorkan bahawa variasi lanjut dalam konfigurasi harus dikaji untuk meningkatkan lagi keberkesanan penukar haba busa logam bersirip yang bersaiz padat.

ACKNOWLEDMENTS

I’d like to express my gratitude to everyone who have contributed to my successful completion of this report. My heartfelt thanks to my supervisor Dr. Setyamartana Parman for accepting me and guiding me into completion of this project from the start.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

PPI	Pores per inch
ε	Porosity
RPM	Rotation per minute
PMMA	Polymethyl Methacrylate
EDM	Electrical discharge machining
TS	Test Section
Re	Reynolds number
ΔP	Pressure drop (Pa)
ρ	Density of fluid (kg/m^3)
V	Average velocity of fluid (m/s)
h	Heat transfer coefficient (W/m^2.°C)
Nu	Nusselt number
μ	Dynamic viscosity of fluid (kg/m.s).
A	Convective heat transfer surface area (m^2)
C_p	Specific heat capacity of fluid (J/kg.°C)
$\dot{V}$	Volumetric flow rate of fluid (m^3/s).
$\dot{m}$	Mass flow rate of fluid (kg/s)
k_c	Thermal conductivity of fluid (W/m.°C)
T_w	Average wall temperature (°C)
T_{in}	Average inlet temperature (°C)
T_{out}	Average outlet temperature (°C)
D_h	Hydraulic diameter (m)
W	Pumping power (W)
Q	Total heat transfer rate (W)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

When a device that is in thermal contact between different mediums of varying temperatures and involved in the operation of heat energy transfer between them, it is commonly referred to as a heat exchanger or heat sink. There is no external heat and work interactions being involved in the processes for most of the time. The most common use for heat exchangers involve heating and cooling processes which may sometimes include the condensing and evaporating of the fluid of interest. Besides that, heat exchangers have also been observed to be used in heat recovery and rejection processes as well. Hence, it is safe to say that heat exchangers are used widely in many engineering systems and products and are a crucial element.

In a majority of the heat exchangers, the transfer of heat occurs through a separating wall in either a continuous manner or just momentarily. Except for a select few, in which there is direct transmission of heat between the fluids.

Since the usage, design method and equipment type vary for the heat exchangers, some classifications are made. Some common classification examples used are as below.

- The type of transfer processes regarding the thermal energy.
- The number of fluids involved in thermal energy transfer.
- The heat transfer mechanism used by the heat exchanger.

Based on their construction type and also the flow arrangements the heat exchangers can be further classified. Besides that, it can also be classified into compact and non- compact heat exchangers based on their volume to effective surface area ratio. Further details on the classifications can be referred in Fig. 1.1. (Shah & Sekulic, 2003)

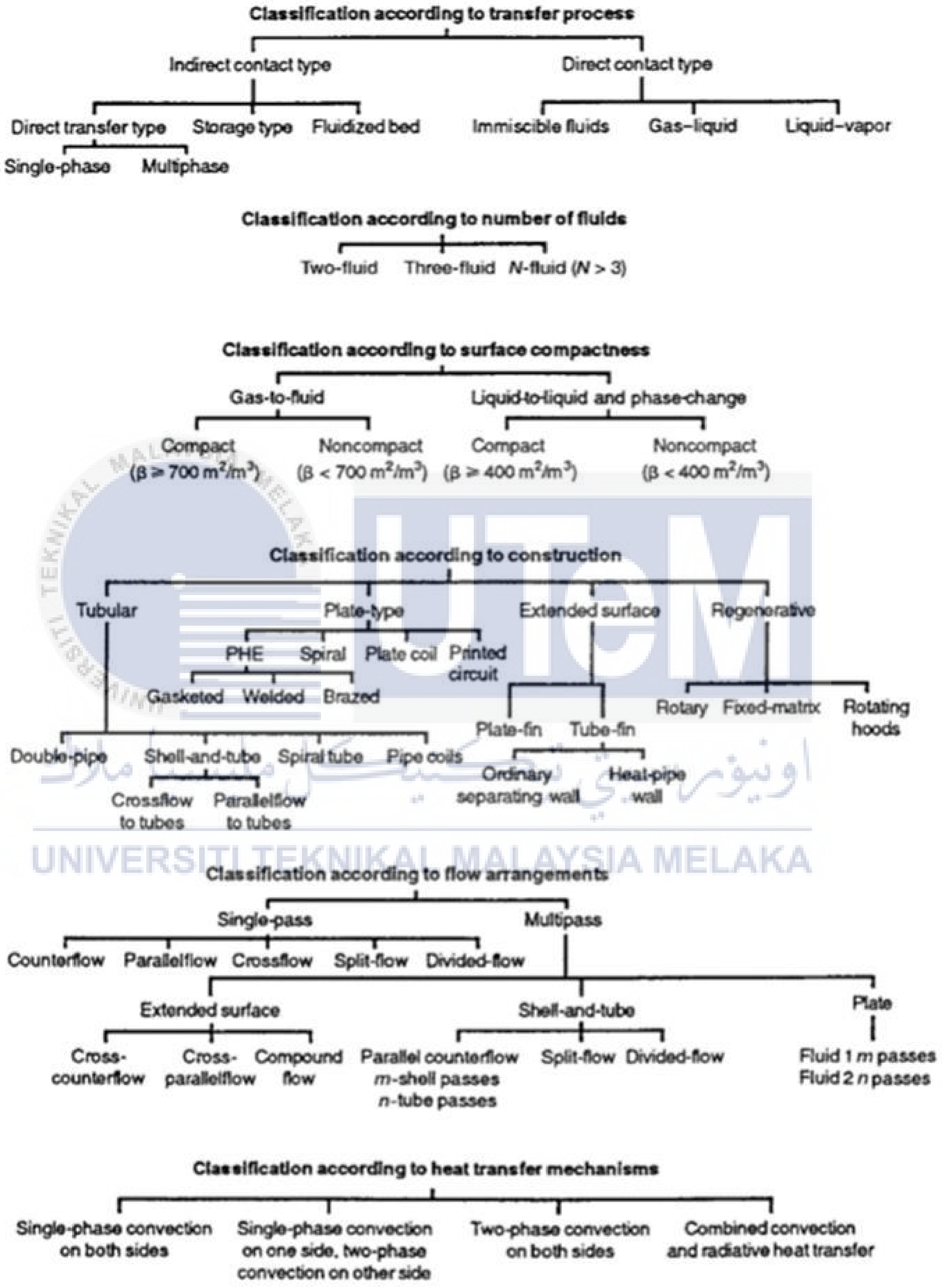

Figure 1.1: Classification of heat exchangers (Shah & Sekulic, 2003)

1.2 Problem Statement

In recent years, major strides have been made in regards to heat exchanger design and manufacturing. This is due to the fact that the optimization of heat exchangers is of paramount importance in regards to saving energy and decreasing the cost. One of the ways to achieve this goal is by enhancing the air-side heat transfer of the heat exchangers in an attempt to improve its thermal effectiveness. (Mobtil, Bougeard, & Russeil, 2018).

The air-side of the heat exchanger is where the thermal resistance is at its highest when it comes to the transfer of heat to the air from the heat exchanger. Fins are usually added here to further enhance the rate of heat transfer. Examples of enhancement techniques developed and being used recently are louvered fins and slit fins with their complex interrupted designs, vortex generators or a combination of both. As new and better designs are being continuously sought after, open-cell metal foam has been singled out as highly potential replacement for the conventional fins due to its unique structural and thermal properties. (Huisseune, De Schampheleire, Ameel, & De Paepe, 2015).

As complex and innumerable in designs it might seem when it comes to optimizing heat exchangers, it can greatly help in reducing the usage of space and also the cost of materials used in fabricating the heat exchangers. Along with that is the improvement in effectiveness of the heat exchangers. By increasing the effectiveness, less power is required to run the heat exchanger and less material is needed to fabricate it, both resulting in significant cost savings. (Catton, 2010).

Hence, it can be seen that the optimization of heat exchangers is essential in current times due to its wide range of application in various fields. One of the ways to achieve this is by reducing the size of the heat exchanger while being able to display a good performance. By doing so, it will result in reduced material usage and cost effectiveness as well as for suitability in small scale applications with minimal compromise in the heat exchanger performance. Thus, the development of a compact heat exchanger is in order, particularly, from open cell metal foam. Researches have suggested that the unique thermal and structural properties of the open-cell metal foam will result in an improved heat exchanger performance.

1.3 Research Objectives

1. To develop an in-house small scale wind tunnel as the test rig to investigate the performance of the compact finned heat exchanger based on open-cell copper foam.
2. To conduct experimental analysis of the performance of the compact heat exchanger based on finned open-cell copper foam with varying configuration.

1.4 Scope of Research

A compact heat exchanger utilizing open cell copper foam fins will be developed and the performance will be tested experimentally along with analysis and discussion of the results. For this experimental analysis, a small scale in–house wind tunnel will be developed to function as the test rig for the process of collecting the experimental results of the compact heat exchanger like the air and wall temperatures as well as the pressure drop across the heat exchanging device. In addition to that, the design of the compact heat exchanger will also be varied by altering the placement of the copper foam fins and aluminium fin. This is done to analyse the difference of the compact heat exchangers performance for varying configurations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review on open-cell metal foam and its applications, performance of open-cell metal foam based heat exchangers, influence on the open-cell metal foam heat exchangers performance due to the parameters and metal foam properties

2.2 Open cell Metal Foam

A part of cellular materials, open-cell metal foam are made of cell structures. This cell structures are made by the conjugation of the solid ligaments resulting in a three- dimensional array of irregular or regular shaped polyhedral cells. Whereas a considerable amount of the open-cell metal foams bulk volume is filled with moving fluid (void volume), typically air. (Beer, Rybár, & Kaľavský, 2019).

The open-cell metal foam possesses the properties that are typical of a well- devised heat exchanger (Boomsma, Poulikakos, & Zwick, 2003). It has a relatively low weight and material usage due to its high volumetric porosity as more than 85% of the structure is usually filled with a flowing fluid like air. Besides that, it also has a high specific surface area and in return a high interaction area between the metal struts and the fluid flowing through it. The complex network of the solid ligaments also provides a tortuous flow path which promotes excellent fluid mixing of the coolant flowing through it. In addition, the usage of metal with high thermal conductivity like aluminium or copper to fabricate the open-cell foam structures also helps greatly in increasing the overall effective thermal conductivity (Huisseune, De Schampheleire, Ameel, & De Paepe, 2015). Hence, replacing the conventional fins in heat exchanger with open-cell metal foam can greatly alter its performance by means of improving the convective heat transfer of the dry air flowing over it. (Hu, Weng, Zhuang, Ding, Lai, & Xu, 2016).

The points made about the unique properties of the open-cell metal foam is further referenced by other researches too. Mahjoob and Vafai (2008) state that the conductive heat transfer of the metal struts along with the convective heat transfer from the fluid flowing through it due to the high surface-to-volume ratio helps in enhancing the heat transfer rate. Hamadouche, Nebbali, Benahmed, Kouidri, and Bousri (2016) echo this point by stating that the solid ligaments normal to the fluid flow direction causes disruption on the interacting surfaces and enhances flow mixing, whereas the conductive heat transfer is further improved by the solid ligaments. Xia, Chen, Sun, Li, and Liu (2017) also state that the tortuous flow path of the three-dimensional pore structure along with the increase in effective surface area are responsible for the enhancement of heat transfer in porous foam materials.

The nature of convective and conductive heat transfer in porous foam materials is complicated as a result of their unique structural properties. Hence, there are several parameters involved in the altering of their conductive and convective heat transfer properties. Some examples are porosity, the material used and sintering (Ma et al., 2016). Haack, Butcher, Kim, and Lu (2001) states that interactions between the coolant and metal foam along with the quality of metal-to-foam bond are found to be important in the heat transfer enhancement of metal foam materials.

2.3 Applications of Open-cell Metal Foam

In a general sense, metal foams due to their porous nature are commonly utilized in ultralight structures where a high strength, rigidity and toughness is required (Lu, Stone, & Ashby, 1998). Apart from being utilised in light weight structures with high structural strength requirement, metal foam are also used as flow conditioners, sound and shock absorbers and fuel combustion enhancers.(Boomsma, Poulikakos, & Zwick, 2003) Besides that, metal foam are also used in lithium-ion batteries as electrodes and as fire retardant material. (Beer, Rybár, & Kaľavský, 2019).

When concerning the field of thermal engineering, they are used in heat exchangers as they are relatively compact along with having a very good thermal conductivity (Beer, Rybár, & Kaľavský, 2019). Due to their heat transfer enhancing properties, open-cell metal foam are used in cryogenic and multi-functional heat exchangers, heat exchanger for airborne devices as well as in heat engines as a regenerator (Lu, Stone, & Ashby, 1998). Metal foams are also heavily utilised as thermal barriers or heat shields in buildings and vehicles to protect them from overheating by dissipating or absorbing the heat. (Mahjoob, & Vafai, 2008).

A particular field of application that can benefit greatly from the unique thermal and structural properties of open-cell metal foam is electronic devices. For example, microprocessors in electronic devices are greatly affected by the heat generated and in return can affect the performance of the electronic device. Due to the fact that most

electronic devices are relatively small in size, a compact heat exchanger with reduced size and high thermal conductivity to provide cooling is crucial. Hence, open-cell metal foam based heat sinks for electronic devices seems propitious at the moment, especially open-cell metal foams made of aluminium with their display of high thermal conductivity and low pressure drop. (Hamadouche, Nebbali, Benahmed, Kouidri, & Bousri, 2016).

The unique thermal and structural properties of open-cell metal foam does not only limit it to thermal engineering applications like compact heat exchangers. There are also research being done on using porous foam material for porous radiant burners (Mujeebu, Abdullah, Bakar, Mohamad, & Abdullah, 2009) and volumetric solar receivers to increase their thermal performance. (Chen, Xia, Yan, & Sun, 2017).

2.4 Previous Study on Open-cell Metal Foam Heat Exchangers

Prior to this, multiple studies have been done to gauge the open-cell metal foams performance. These researchers conducted several experiments with different measurement procedures, flowing fluid, experimental apparatuses and metal foam samples to study the hydraulic properties as well as the thermal properties of the open- cell metal foam based heat exchangers.

2.4.1 Performance of Open-cell Metal Foam Heat Exchangers

Several research have been done to analyse the heat exchangers performance when utilising open-cell metal foam and then compared with either their non-foam counterpart or with conventional heat exchangers available on the market. Some interesting observations have been noted when this comparisons were made. Firstly, there are studies that have shown the metal foam based heat exchangers to be superior like the study done by Boomsma, Poulikakos, and Zwick (2003), in which under constant pumping power requirement and various coolant flow velocities, the aluminium foam based heat exchanging device displayed thermal resistance that were 3 to 2 times lower in comparison to several good commercially available heat exchanging device that were tested in prior to this study. Apart from the superior heat transfer performance from the aluminium foam heat exchanger, it was also noted that there was a significant improvement in efficiency while operating under identical conditions when compared to some of the commercially available heat exchangers. In another experiment conducted using aluminium foam blocks and solid aluminium blocks by Hamadouche, Nebbali, Benahmed, Kouidri, and Bousri (2016), it was observed that the more porous aluminium foam blocks had lower pressure losses and a heat transfer performance that was two times better that the solid aluminium block. Elayiaraja, Harish, Wilson, Bensely, and Lal (2010) carried out an experiment comparing between copper foam heat exchanger and conventional aluminium heat exchanger under identical operating conditions. They noted that the high conductivity of the cell-wall and large available heat transfer area of the open-cell metal foam results in an extraordinary thermal performance and greatly improve the cooling capability of the heat sink. This was evident by the result obtained from their study in which the copper foam heat exchanger exhibited heat transfer that is 35% to 45% larger than the conventional aluminium heat exchanger.

Besides that, there are also studies that have shown the open-cell metal foam based heat exchangers to be inferior as shown in the study by Byon (2015), in which the aluminium foam heat sink performed more effectively to the pin-fin heat sink of similar porosity at low coolant flow velocities. But the pin-fin heat sink seemed to be performing better at larger flow velocities due to better fluid conductance and larger effective heat transfer area when compared to the aluminium foam heat sink. Wang, Kong, Xu, and Wu (2019) carried out an experiment using finned copper foam heat sinks and conventional finned heat sinks. It was observed that the conventional finned heat sinks had pressure drops that were 10 to 20 times lower and also better heat transfer rate. The finned copper foam heat sinks had no noticeable heat transfer advantage and had larger flow resistance resulting in high pressure losses. But it is worth mentioning that the finned metal foam has promising application prospect such as being suitable for use in narrow and confined spaces with height restrictions but less stringent pumping power requirement once the issue of lowering the flow resistance is addressed. Ribeiro, Barbosa, and Prata (2012) also noted similar trends in regards to thermal performance when they carried out their study on microchannel condensers made from open-cell copper foam. The plain fin condenser with identical characteristics had better overall thermal conductance than the copper foam based condenser at a fixed pumping power condition. Although the aluminium foam heat exchanger with its porous nature had a higher surface area per unit volume compared to the aluminium fin heat exchanger, the thermal performance, pressure loss and effectiveness of the aluminium fin heat exchanger is still better in comparison. The reason for the superior heat transfer rate and effectiveness of the aluminium fin heat exchanger was identified to be due to the stronger point wise contact and increased contact availability between the aluminium fin and heat exchanger tubes passing hot fluid in comparison to the aluminium foam filaments. (Sertkaya, Altınısık, & Dincer, 2012)

2.4.2 Influence on the Open-cell Metal Foam Heat Exchanger Performance Due To The Operative Parameters

There are several factors that influences the performance of the open-cell metal foam based heat exchangers. One such factor is the operative parameter when conducting the studies, such as the coolant flow and heat flux. Regarding the coolant flow, most of the previous studies conducted relied on forced convection with some exception that used the cheaper and convenient natural convection method. Elayiaraja, Harish, Wilson, Bensely, and Lal (2010) conducted their study of copper foam heat sink using buoyancy induced convection in which the heat generated by the small engines or electronic components are transferred to the metal foam and transferred to the air by means of convection.

Moving on, a majority of this previous studies were conducted using test rigs that utilised parallel flow cooling or duct cooling. Although this test rigs are mostly horizontal wind tunnels, there are some studies like that conducted by Kamath, Balaji, and Venkateshan. (2013), in which a vertical wind tunnel with a vertical duct containing the test specimen and a bottom mounted axial fan is used. In the study done by Boomsma, Poulikakos, and Zwick (2003), as the coolant velocity was increased from zero to the maximum allowable setting, the heat transfer rate started increasing monotonically. But in the study conducted by Hamadouche, Nebbali, Benahmed, Kouidri, and Bousri (2016), the pressure drop across the aluminium foam blocks increased for increasing air velocity in a quadratic fashion suggesting that there is a more prominent influence on the pressure drop by the coolant flow. The thermal performance is also affected by coolant flow as seen in the study by Mancin, Zilio, Diani, and Rossetto (2012), in which the pressure losses and heat transfer rate is seen increasing with an increase in the air mass flow rate. Besides that, the heat flux imposed doesn’t have a sizeable impact on the heat transfer as seen in the study by Mancin, Zilio, Cavallini and Rossetto (2010) and Mancin, Zilio, Diani, and Rossetto (2012). They both concluded that the heat transfer coefficient depends on the air mass flow rate instead of the heat flux being supplied. The same trend is observed even when using different cooling medium such as in the study conducted by Sertkaya, Altınısık, and Dincer (2012), the pressure losses increased with increasing refrigerant velocity but the effectiveness of the heat exchanger seemed to be decreasing.

A new method being used recently for studying the performance of open-cell metal foam is jet impingement cooling and has been receiving much notice lately. The synergy of the aforementioned cooling technology is said to probably give rise to a significant thermal performance. Compared to duct flow, the cooling performance provided by jet impingement is said to be superior due to formation of thin boundary layer on the heated surface resulting in higher convective heat transfer. The heat transfer rate in a jet impingement cooling may be a culmination of many factors but the geometry of the jets cross section is said to not have a large impact on the heat transfer rate of metal foam heat sinks as concluded in the research done by Byon (2015), allowing for the convenient development of test rigs utilising jet impingement cooling.

2.4.3 Influence on the Open-cell Metal Foam Heat Exchanger Performance Due To The Metal Foam Properties

The properties of the metal foam have a significant impact on the performance of the metal foam heat exchangers. The properties usually refers to the porosity, pore density, pore size and material. The first property that will be looked at is the porosity. Porosity, ε is a used as way to describe the void or empty spaces for a given material and is found by isolating the void volume from the total volume of the porous medium. The effect of porosity was observed in the study done by Mancin, Zilio, Cavallini and Rossetto (2010), in which the heat transfer coefficient of aluminium foam heat exchangers increased for decreasing porosity for a fixed pore density. This trend is similar to that of the study conducted by Mancin, Zilio, Diani, and Rossetto (2013), in which the heat transfer of both the aluminium and copper foam heat exchangers increased when the porosity was decreased for constant pore density. The possible explanation given for this trend was lower porosity results in a higher surface area per unit volume which gives rise to a higher heat transfer area and results in the heat exchanger having a better thermal performance capability. The importance of surface area per unit volume in the overall performance of the metal foam heat exchangers is reiterated in the experiment done by Mancin, Zilio, Diani, and Rossetto (2012), in which the copper foam heat exchanger with lower porosity at a fixed pore density showed the higher interstitial heat transfer coefficient due to the higher heat transfer area and relative density. The pressure losses along with the heat transfer are also affected by the porosity of the metal foam. Ribeiro, Barbosa, and Prata (2012) did an experimental study on microchannel condensers made of open-cell copper foam and found that the more porous the copper foam, the smaller the pressure losses. This is due to the fact that the flow obstructions will reduce as the porosity of the metal foam increases. In the study done by Boomsma, Poulikakos, and Zwick (2003), it was observed that the aluminium foam based heat exchanger with the lowest porosity had the largest pressure loss while the most porous sample generated the lowest pressure drop. This trend again is similar to that observed in the experiment conducted by Kamath, Balaji, and Venkateshan. (2013), in which the porosity of the aluminium metal foam heat exchanger is directly proportional to the pressure losses.

Another property of open-cell metal foam that is usually taken into consideration is the pore density or also known as PPI (pores per inch) which is simply the means to describe the number of pores on the metal foam. In addition to that, there is also pore size which is closely related pore density and porosity. Mancin, Zilio, Diani, and Rossetto (2013) conducted an experiment in which the porosity of both the aluminium and copper foam heat exchangers were kept constant and the PPI was varied.

The pressure drop increase as the PPI was increased due to the reduction in permeability. The reduction in permeability for higher pore density and increase in the pressure losses was also observed in the study done by Mancin, Zilio, Diani, and Rossetto (2012). They also have stated in their study that the high pressure losses of the copper foam heat exchanger with high pore density is alleviated by the high heat transfer surface area value. In the study conducted by Ribeiro, Barbosa, and Prata (2012), it was found that the pressure losses is directly proportional to the pore density as higher pore densities relates to smaller pore size that can lead to higher surface area and higher friction factor as well as a more tortuous flow from the narrower flow path. Increasing the pore density also resulted in the improvement of the air-side heat transfer as the interstitial area is increased. The importance of pore size is further highlighted in the study conducted by Haack, Butcher, Kim and Lu (2001). They found out that smaller pore sizes resulted in higher pressure losses as well as higher heat transfer rate. The thermal performance of the metal foam heat exchanger with larger pore size was excellent with relatively low pumping power for higher coolant flow rates. The type of metal foam used in fabrication of heat exchangers also play a vital role in its performance as demonstrated by Mancin, Zilio, Diani, and Rossetto (2013). They noticed that the coppers high thermal conductivity value helped in improving the thermal performance of the copper foam heat exchanging device when compared to the aluminium foam heat exchanging device.

2.4.4 Influence on the Open-cell Metal Foam Heat Exchanger Performance Due To The Geographical Parameters

Geometrical parameters refer to the size and shape of the metal foam heat exchanging device. Regarding the size, it is usually referred to as the height, thickness or length of the sample depending on the orientation. Kamath, Balaji, and Venkateshan. (2013) conducted an experiment on aluminium foam heat exchangers and found out that the heat transfer is enhanced significantly for use of thicker aluminium foam for a given flow velocity. But the increase in aluminium foam thickness had no significant influence on the pressure losses. Feng, Kuang, Wen, Lu, and Ichimiya (2014) conducted a study using finned aluminium foam heat sinks and aluminium foam heat sinks. It was noted that the heat transfer for the finned aluminium foam raised with an increase in the metal foam height due to the higher heat exchange area between the finned aluminium foam heat sink and cool air. The pressure drop also increased exponentially with decreasing foam height for same volumetric flow rate due to the smaller flow area and higher flow velocity in the foam. The pressure trend is similar to that witnessed by Wang, Kong, Xu, and Wu (2019) in their study. As the height of the finned copper foam were reduced, the pressure losses increased for all the heat exchanger. But the thermal performance of the finned copper foam were enhanced when the foam height was reduced instead. The explanation given was that the increased height of the metal foam with low thermal conductance made the heat transfer from the heater at bottom to the top of the heat exchanger more difficult although the heat exchange area is larger. The same phenomena is encountered by Mancin, Zilio, Diani, and Rossetto (2013) in their study using aluminium and copper foam heat exchangers. The higher foam finned surface efficiency of metal foam heat sink with half the height and half the heat transfer area allowed it to still have a higher heat transfer coefficient.

Regarding the shape of the metal foam heat exchangers, a study done by Feng, Kuang, Wen, Lu, and Ichimiya (2014) addressed this by comparing the performance of regular flat faced aluminium metal foam heat sinks with finned metal foam heat sinks made by inserting strips of aluminium foam fins in between aluminium plate fins. The thermal performance of the finned aluminium foam heat sinks was about 1.5 to 2.8 times higher than that of the flat faced aluminium heat sinks for a given pumping power condition or flow velocity.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the development of the heat exchanger test rig and its parts and their specifications are discussed. The instrumentation needed in this project also been discussed in this chapter.

3.2 Development of Heat Exchanger Test Rig

For the process of experimental analysis on the compact finned open-cell metal foam heat exchangers, a test rig had to be developed. Hence, the development of an in-house small scale open circuit wind tunnel using forced convection method for heat transfer and pressure drop experimentation of the heat exchangers was proposed and carried out. The heat exchanger test rig will be assembled using smaller components that are developed or acquired separately. After the design for the components involved in the heat exchanger test rig was finalised, the computer-aided design (CAD) model for the components were done and assembled. Using the design specification provided by the CAD modelling, the components were fabricated or acquired and assembled to form the finished heat exchanger test rig

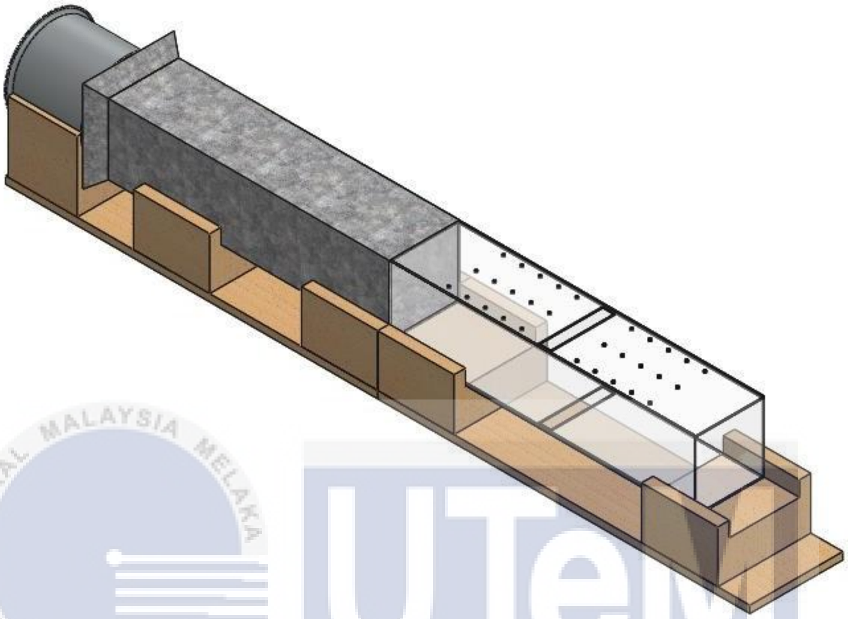

Figure 3.1: Computer-aided model of the in-house small scale wind tunnel (Heat exchanger test rig).

3.2.1 Axial Blower

An axial blower was chosen to help in the process of pumping the coolant (air) into the channel of the heat exchanger test rig. The axial blower fan has a length of 260 mm and a fan blade diameter of 250 mm and is mounted at the front of the settling duct with the back facing the open surrounding of the laboratory. An electric fan speed regulator (KQ409) is used to vary the power input to the axial blower and facilitate in the process of changing the flowrate of the coolant (air).

3.2.2 Settling Duct

The purpose of the settling duct is to help in reducing the turbulence and also flatten out the velocity profile of the air. This is crucial for a more accurate reading during the performance measurement of the compact heat exchanger. Since this settling duct will not be used to house the heat exchanger or any sensors, a lightweight, easy to fabricate and cheap material is sufficient. Hence, galvanised sheet metal was chosen for the fabrication of the settling chamber. The required design for the settling duct is drawn onto the galvanised sheet metal before being cut using a sheet metal shear and taped together using Butyl tape. The settling duct is 230 mm wide, 230 mm high, and 920 mm long with a square projection at the front to connect the settling duct to the blower.

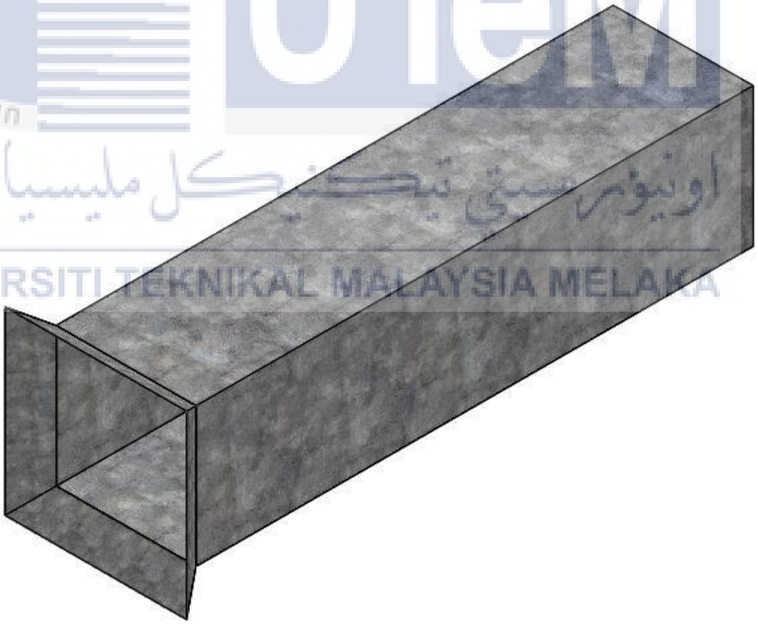

Figure 3.2: Computer-aided model of the settling duct

3.2.3 Test Section

The test section is where the compact heat exchanger will be placed along with the sensors when the experimental work is being carried out. The dimensions of the test section are width 230 mm, height 230 mm, and length 1000 mm with a rectangular cut- out of width 220 mm and length 40 mm in the middle of the test section. This cut-out will aid in the insertion of the compact heat exchanger with its housing. The top surface of the test section has 30 small holes of the diameter 8 mm drilled into it for the convenient placement of the sensors (Pitot tube and thermocouples) for measurement purposes. The material chosen for the fabrication of the test section is Polymethyl methacrylate (PMMA) or also known as acrylic. The reason for the selection of acrylic is due to the fact it’s lightweight, shatterproof and cheaper in comparison to glass as well as being cheaper and easier to fabricate. Besides that, the test section has to be also fabricated of a material with low thermal conductance. The acrylic sheet was cut into the required dimension and shape by using laser cutting method, while the small holes on the top surface were drilled using a benchtop drill press. The cut acrylic boards were then assembled together and held in place using L-brackets and bolts at the edges of the acrylic boards along with silicone sealant. In order to minimise heat losses to the surrounding and transfer of heat between the heating cartridge and the wall of the test section, ceramic fibre blanket insulation is used to cover the inner surface of the test section.

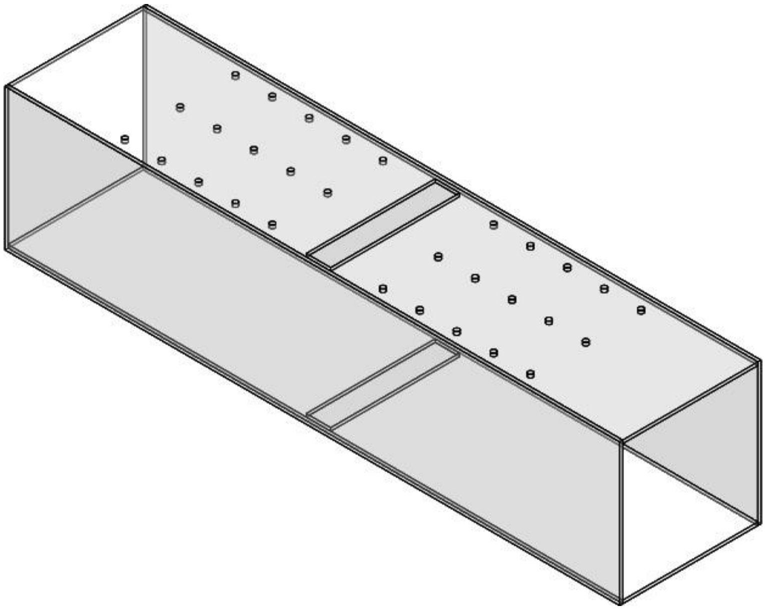

Figure 3.3 Computer-aided model of the test section

3.2.4 Base

A base is required to hold all the components in place as well as to provide the test rig with a certain degree of mobility. Due to several factors, the material chosen for the fabrication of the base is plywood. Compared to metal, plywood is cheaper, lighter and easier to work with. In addition, the plywood has a higher damping capacity than metal and will help greatly in dampening any vibrations produced by the operation of the blower fan. The base has a dimensions of width 300 mm, height 120 mm, and length 2400 mm and is held together using nails and wood adhesive.

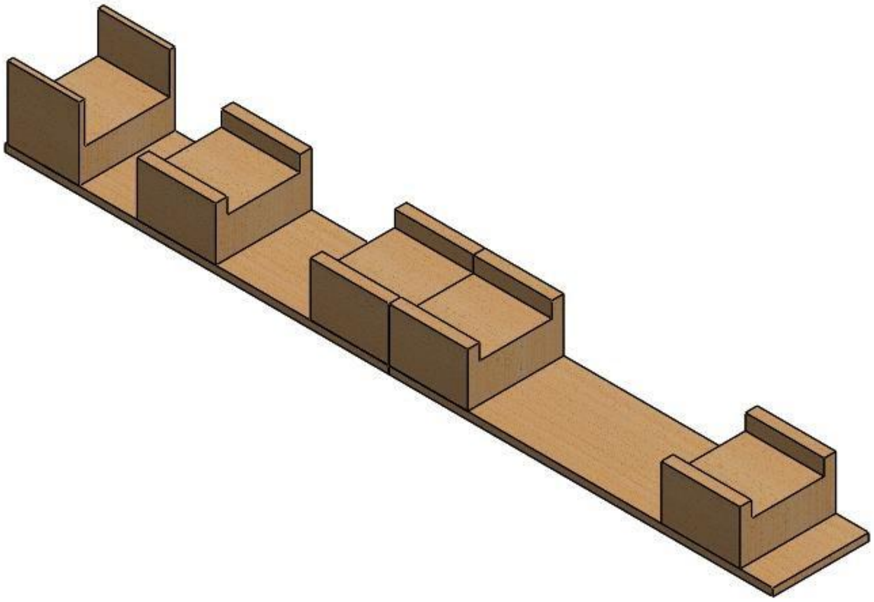

Figure 3.4: Computer-aided model of the base

3.2.5 Heat Exchanger Housing

The purpose of the housing is to hold the finned copper foam and aluminium fins in place as well as to hold the heating cartridges in place. The housing for the open-cell metal foam heat exchanger is manufactured from aluminium with dimensions of height 240 mm, width 200 mm and thickness 32 mm. Aluminium was chosen due to it being lightweight, cheaper and more thermally conductive in comparison to stainless steel. Two holes measuring 12.5 mm in diameter were bored at the bottom and top of the housing for the placement of two cylindrical heating cartridges.

3.2.6 Temperature Controller

The temperature controller is a component that controls the power supply of the cartridge heaters to regulate the heat flux given to the heat exchanger. The cartridge heaters are controlled by a Shimaden SR1 series digital controller and a Celduc heat sink.

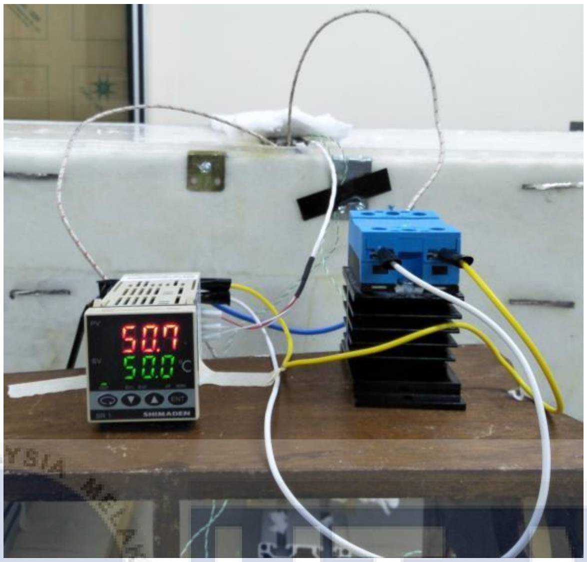

Figure 3.5: Shimaden SR1 series digital temperature controller with Celduc heat sink

3.2.7 Cartridge Heater

To provide heat energy to the heat exchanger, two 600 W cylindrical cartridge heaters with a diameter of 12 mm and a length of 20 cm are employed. The cartridge heater, which can achieve temperatures of up to 450°C, will be utilised in conjunction with the temperature controller to give a continuous heat flux to the sample via the temperature controller. Heat is transferred conductively through the stainless steel shell to the finned copper foam.

3.3 Instrumentation and Measurement

3.3.1 Pressure Measurement

Pressure instrumentation is necessary to determine the pressure losses across the device by measuring the pressure at the front and back of the sample. In order to measure the pressure, a pitot tube and a digital manometer will be used. The Pitot tube used is a Testo 0635 2145 L-Type Stainless Steel Pitot Tube with a length of 350 mm and a diameter of 7 mm, type Testo 0635 2145 L-Type Stainless Steel Pitot Tube. The Pitot tube will be used with the Testo 521-1 digital manometer. The digital manometer has a measuring range of 0 to 100 hPa, a resolution of 0.01 hPa, and an accuracy of 0.2 percent of the full-scale value. The Pitot tube is inserted through one of the 30 tiny holes with a diameter of 8 mm at the top of the test section surface and held in place with a retort support to measure pressure.

Temperature instrumentation is required for the purpose of measuring the temperature of the sample surface as well as the temperature of the cooling fluid in the test section at various points.

Figure 3.6: Pitot tube (Testo 0635 2145 L-Type) with digital manometer (Testo 521-1)

3.3.2 Temperature Measurement

At various places throughout the test section, temperature instrumentation is required to measure the temperature of the sample surface as well as the temperature of the cooling fluid. Several Exposed Welded Tip K-type Thermocouples are used to make temperature measurements. The thermocouples have a Class 1 tolerance and can operate in a temperature range of -75°C to +260°C, according to the IEC 60 584-2:1995. The thermocouples are used in conjunction with a data logger device from Omega, the model USB TC-08 thermocouple data acquisition module, which is capable of sensing 8 thermocouples simultaneously and capturing 10 readings per second with a resolution of 20 bits. The thermocouples are inserted with the tips of the thermocouples through one of the 30 small holes of diameter 8 mm at the top of the test section surface.

In the test section, the thermocouple is either positioned on the copper foam of the heat exchanger or hanging in mid-air.

Figure 3.7: Data logger (USB TC-08) with K-type thermocouple

3.3.3 Flow Measurement

To aid in the heat transfer process of the heat exchanging device, air is used as the cooling fluid. With the help of a high-speed blower, ambient air is pumped into the heat exchanger test equipment. The air enters the test section and comes into contact with the sample in the centre before being discharged into the surrounding atmosphere through the hole at the end. The axial fan motor's power input is adjusted to change the air velocity. The Pitot tube (Testo 0635 2145 L-Type Stainless Steel Pitot Tube) and digital manometer are used to measure the coolant's localised flow rate and velocity (Testo 521-1).

3.4 Development of Open-Cell Copper Foam Heat Exchanger

In the aluminium heat exchanger housing, the compact finned copper foam heat exchanger is formed by inserting the aluminium fins near to the copper foam fins. The copper foam fins measure 200 mm in height, 5 mm in width, and 20 mm in thickness, while the aluminium fins measure 200 mm in height, 1 mm in width, and 20 mm in thickness. Pore density is 60 PPI, porosity is 0.93, and pore size is 0.556 in copper foams. Open-cell copper foam is utilised instead of aluminium foam because it has a higher thermal conductivity. Because of the greater thermal performance, copper foam with a higher pore density, low porosity, and small pore size was chosen, as described in the literature review. Because the components are not kept in place by glue or bonding agent, but by means of transition fitting, both the copper foam fins and the aluminium fins are created utilising wire cut electrical discharge machining (EDM) for a high precision fabrication method. Vary the configuration or positioning of the copper foam fins and aluminium fins to change the finned heat exchanger design. The copper foam fins and aluminium fins are put sequentially starting from the sides in the first configuration, employing 29 copper foam fins and 28 aluminium fins.The number of aluminium fins is kept constant at 28, but the number of copper foam fins is decreased by almost half to 15 by removing them selectively and leaving a gap in place in the second configuration.

Figure 3.8: Configuration 1 of compact finned copper foam heat exchanger

Figure 3.9: Configuration 2 of compact finned copper foam heat exchanger

3.5 Experimental Setup

3.5.1 Thermal and Hydraulic performance of Heat Exchanger

The experimental examination of the compact finned copper foam heat exchanger was carried out after the creation of the heat exchanger and the test equipment was completed. The temperature controller attached to the cartridge heaters was used to deliver a consistent heat flux to the heat exchanger, which was placed in the centre of the test section. Throughout the testing, the cooling fluid, air, was pulsed through the test portion at varied speeds ranging from 0.7 m/s to 3 m/s for both configurations of the small finned copper foam heat exchanger. Using the data logger and the given software, the K-type thermocouples were used to record the temperature of the cooling fluid as well as the temperature across the copper foam wall of the heat exchanging device. Three thermocouples were placed at the test section's intake and three more at the outlet, with six thermocouples placed on the heat exchanger's copper foam wall. The pressure drop is calculated by utilising a digital manometer and a Pitot tube between the inlet and outflow to differentiate the pressure of the cooling fluid in the test area.

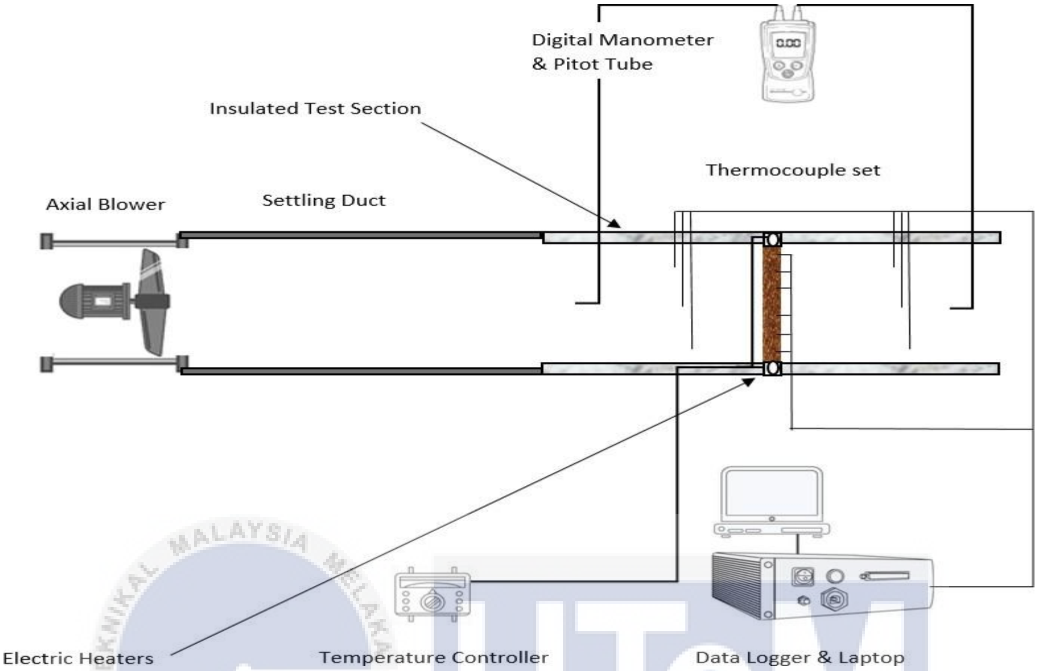

Figure 3.10: Schematic diagram of experimental setup used to study the performance of compact finned heat exchanger using open-cell copper foam

CHAPTER 4

RESULTS & DISCUSSION

4.1 Pressure Drop Analysis

The Reynolds number is a non-dimensional flow factor that is widely used to compare heat exchanger hydraulic parameters. When both heat exchangers are placed in the test section, the Reynolds number of the cooling air is computed using equation (1). Because of the increased flow resistance, the cooling air flow velocity is lower when the first configuration of the heat exchanger is utilised than when the second configuration is employed.

Table 4.1.1: Properties of cooling fluid flow in test section channel for configuration 1

Airflow	Velocity, V (m/s)	Reynolds Number, Re
1	0.7	9217
2	0.9	12144
3	1.4	19349
4	1.6	22082
5	1.8	24960

Table 4..1.2: Properties of cooling fluid flow in test section channel for configuration 2

Airflow	Velocity, V (m/s)	Reynolds Number, Re
1	1.0	13744
2	1.7	23639
3	2.1	28551
4	2.4	32539
5	2.6	35517

One of the most significant parameters to consider when building a heat exchanger device is the amount of work required to pump the cooling fluid through it. Boomsma, Poulikakos, and Zwick (Boomsma, Poulikakos, & Zwick, 2003) As a result, the hydraulic features of the constructed heat exchanging device were experimentally evaluated at various coolant flow rates, and the pressure drop across the heat exchangers, P (Pa), was graphically plotted versus the Reynolds number, as shown in Figure 4.7.

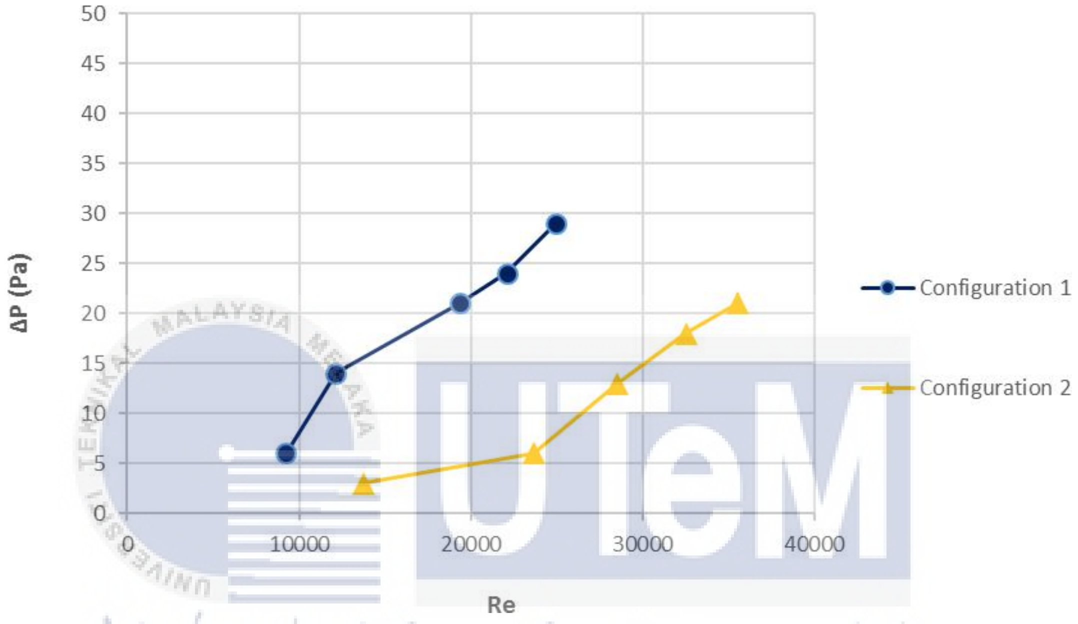

Figure 4.1: Pressure drop, ΔP plotted as a function of Reynolds number, Re for both configuration of the compact finned copper foam heat exchangers.

Figure 4.7 shows that the pressure drop across the heat exchanger for both designs grows in a quadratic fashion as the Reynolds number increases, which is a common behaviour for porous materials. The pressure drop for the compact finned copper foam heat exchanger configuration 1 is nearly 5 times greater than the pressure drop for the configuration 2 at the same Reynolds number. This is most likely owing to the lower flow resistance offered by configuration 2 due to the air gaps between the finned copper foams, as opposed to the usage of two times as many finned copper foams in configuration 1, which greatly increases pressure losses.

4.1.1 Comparison with open literature

The results of the current study are compared to the available literature to check if they agree with those of prior similar investigations. Due to their similarities in finned metal foam heat exchanger design to that of configuration 1, the pressure drop, P, and Reynolds number, Re are retrieved from (10) and (8) and compared with the current study.

Table 4.1.1.1: Details of the heat exchanger in open literature used for comparison.

	Present Study	Feng	Wang 1	Wang 2
Thickness (mm)	20	20	15	15
Material	99.99% Copper Alloy	Aluminium alloy	Copper alloy	Copper alloy
Pore Density (PPI)	60	8	10	20
Porosity	0.93	0.96	0.92	0.92

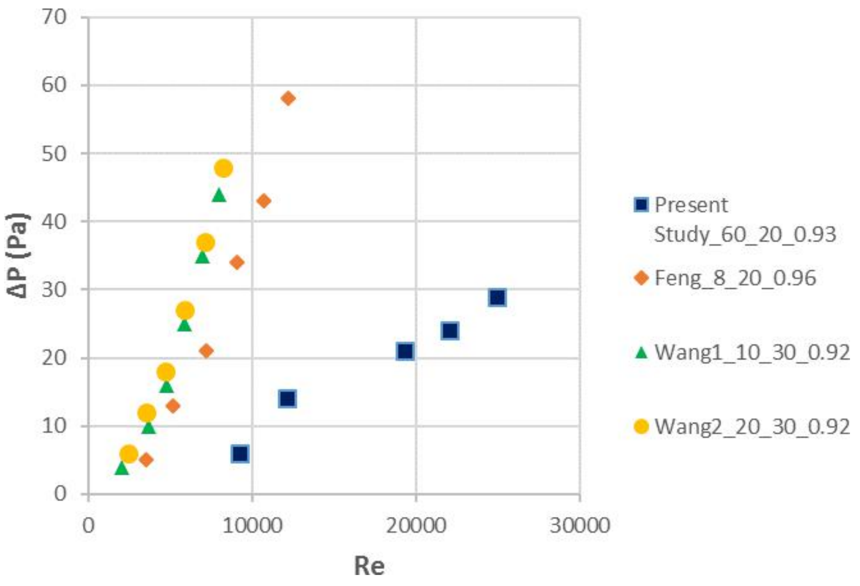

Figure 4.2: Comparison of pressure drop, ΔP against Reynolds number, Re from present study with open literature (Feng is the data reported by Feng, Kuang, Wen, Lu, and Ichimiya (2014) and Wang 1 and Wang 2 are data reported by Wang, Kong, Xu, and Wu (2019))

The labels in the picture are 1_2_3_4, where '1' represents the research reference, '2' represents the pore density, '3' represents the foam thickness, and '4' represents the foam porosity. When compared to open literature data of finned copper foam heat exchangers with lower PPI, the pressure drop for the current study is smaller. This can be explained by the fact that the current study uses an axial blower with backward-curved blades, whereas prior investigations used centrifugal blowers in their test rigs. According to Yu, Zhang, and Qian (2011), centrifugal fans are better suitable for high pressure applications than axial flow fans because they can generate comparatively high pressures. Marchildon and Mody (2005) reinforce this by stating that axial type fans have a minimal pressure rise but centrifugal variations can produce significant pressures.

4.2 Thermal Performance Analysis

The Nusselt number (Nu) is a commonly used dimensionless number used in evaluating and comparing the thermal performance of heat exchangers (1) as given in equation (2).

$$\mathrm{Nu} = \frac{h.D_h}{K_C} \tag{2}$$

h is the average convective heat transfer coefficient (W/m^2.°C) of the heat exchanger, D_h is the hydraulic diameter (m) of the test section and k_c is the thermal conductivity of the cooling fluid (W/m.°C) used. The average convective heat transfer coefficient is as given in equation (3).

$$h = \frac{Q_{EL}}{A.(T_w - T_{in})} \tag{3}$$

Where A is the convective heat transfer surface area (m^2) of the heat exchanger which is the cross-sectional area of the copper foam heat exchanger exposed to the cooling fluid. T_{in} is the average inlet temperature (°C) of the test section and T_w the average wall temperature (°C) of the copper foam heat exchanger. Q_{EL} is the heat transfer rate from the electrically heated test surface (W) which can be expressed as the heat transfer rate to the coolant, Q (W) as shown in the following energy balance equation of equation (4). This assumption is made on the basis there is no significant heat lost from the test section to the surrounding as the surrounding temperature of the laboratory was nearly similar to the outer surface temperature of the test section at the heating section as shown by the digital thermometer.

$$Q_{EL} = \dot{m}.C_p.(T_{in} - T_{out}) \tag{4}$$

ṁ is the mass flow rate of the cooling fluid (kg/s) passing through the test section, while C_p is the specific heat capacity of the cooling fluid (J/kg.°C) and T_{out} is the average outlet temperature (°C) of the test section.

By substituting the equation (4) into equation (3), the heat transfer coefficient, h was found utilising the following equation (5).

$$h = \frac{\dot{m}.C_p.(T_{in} - T_{out})}{A.(T_w - T_{in})} \tag{5}$$

By substituting the equation (5) into equation (2), the Nusselt number, Nu was calculated using the following equation (6).

$$Nu = \frac{D_h}{K_C} . \frac{\dot{m}.C_p.(T_{in} - T_{out})}{A.(T_w - T_{in})} \tag{6}$$

All the calculations are solved using the Engineering Equation Solver (EES) software and the thermo-physical property values of air were acquired by referring to the bulk mean temperature.

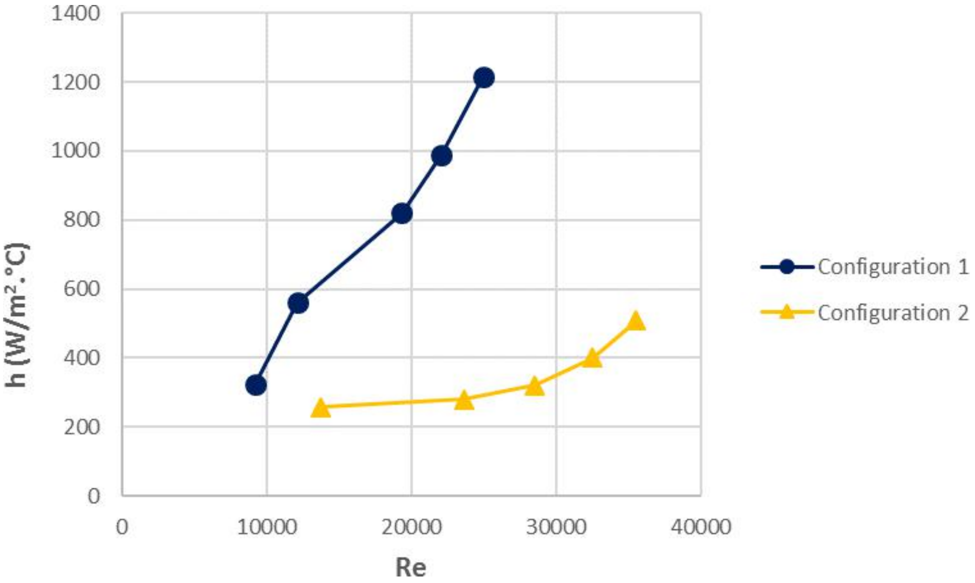

Figure 4.3: Average convective heat transfer coefficient, h plotted as a function of Reynolds number, Re for both configuration of the compact finned copper foam heat exchangers.

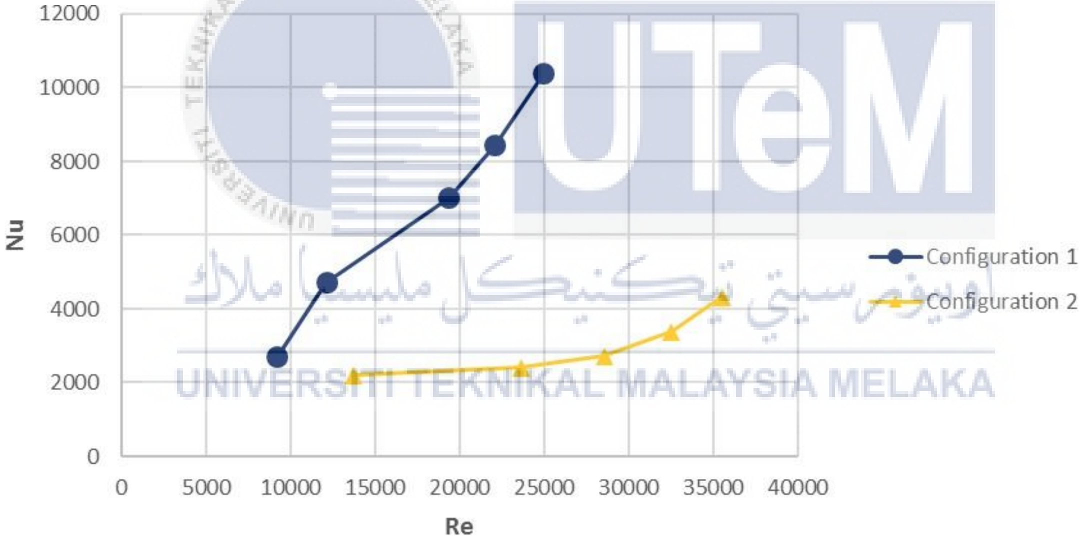

Figure 4.4: Nusselt, Nu number plotted as a function of Reynolds number,Re for both configuration of the compact finned copper foam heat exchangers.

Figures 4.9 and 4.10 show that when the Reynolds number increases, the heat transfer coefficient and Nusselt number both increase, showing that convective heat transmission is superior at higher Reynolds numbers. At the same Reynolds number, the heat transfer in configuration 1 of the compact finned copper foam heat exchanger is 2.5 to 5 times that of configuration 2. This is due to the higher heat exchange surface in configuration 1 compared to configuration 2, which uses more than twice the number of finned copper foam. In configuration 1, the influence of a greater Reynolds number on the heat transfer rate is more pronounced.

4.2.1 Comparison with Open Literature

Comparison with open literature and the present study is done to see if the results obtained is in agreement with previous similar studies done. For this purpose, the Nusselt, Nu and Reynolds, Re number are retrieved from (Wang, Kong, Xu, & Wu, 2019) and (Feng, Kuang, Wen, Lu, & Ichimiya, 2014) and compared with the present study due to their similarities in finned metal foam heat exchanger design to that of configuration 1.

Table 4.2.1.1: Details of the heat exchanger in open literature used for comparison.

	Present Study	Feng	Wang 1	Wang 2	Wang 3
Thickness (mm)	20	20	15	15	15
Material	99.99% Copper Alloy	Aluminium alloy	Copper alloy	Copper alloy	Copper alloy
Pore Density (PPI)	60	8	10	20	30
Porosity	0.93	0.96	0.92	0.92	0.91

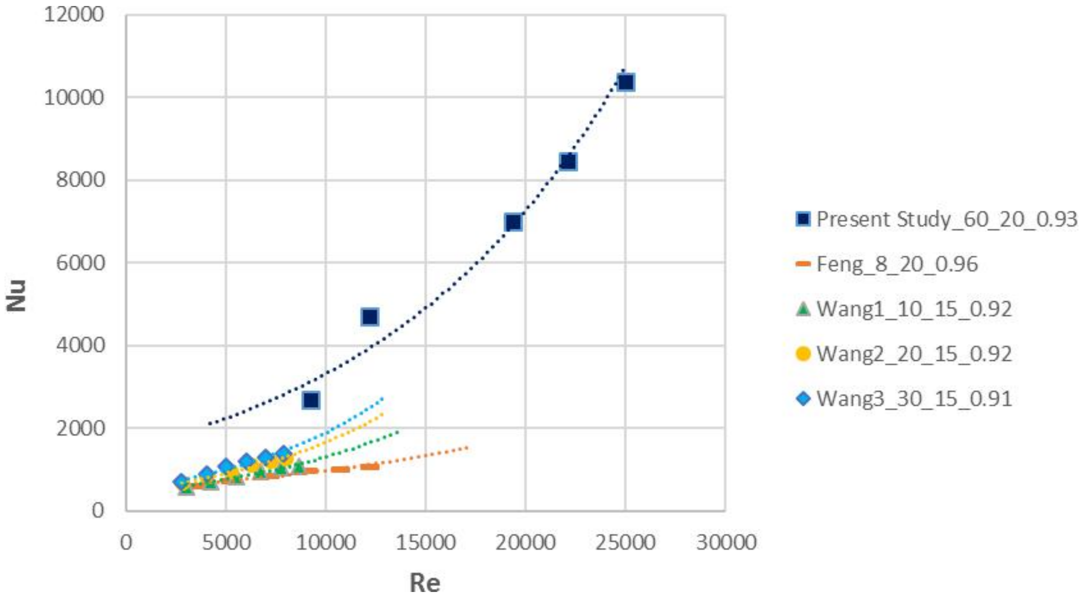

Figure 4.5: Comparison of Nusselt number against Reynolds number from present study with open literature (Feng is the data reported by Feng, Kuang, Wen, Lu, and Ichimiya (2014) and Wang 1, Wang 2, Wang 3 are data reported by Wang, Kong, Xu, and Wu (2019))

The legends in figure are represented as 1_2_3_4, where '1' is the study reference, '2' is the pore density, '3' is the foam thickness and '4' is the foam porosity. The dotted line in the graph represents the best fit curve for all the experimental data values present. The Nusselt number from the open literature are lower than that of the present study due to their lower pore density. The Nusselt number of the present study is almost twice that of the 30 PPI copper foam heat exchanger from previous study with almost similar thickness and porosity proving that the results obtained are reliable to a certain degree.

4.3 Pumping Power Analysis

In regards to designing heat exchangers, the energy required to run the system is consider alongside the thermal performance of the heat exchanging device (Boomsma, Poulikakos, & Zwick, 2003). Hence, for various cooling fluid velocities, the pumping power for the compact finned copper foam heat exchanger is obtained using equation (7).

$$W = \dot{V}.\Delta P \tag{7}$$

ΔP is the pressure drop (Pa) across the heat exchanger measured by differentiating the pressure of the cooling fluid near the inlet of the test section with the pressure near the outlet of the test section while $\dot{V}$is the volumetric flow rate of the cooling fluid (m^3/s).

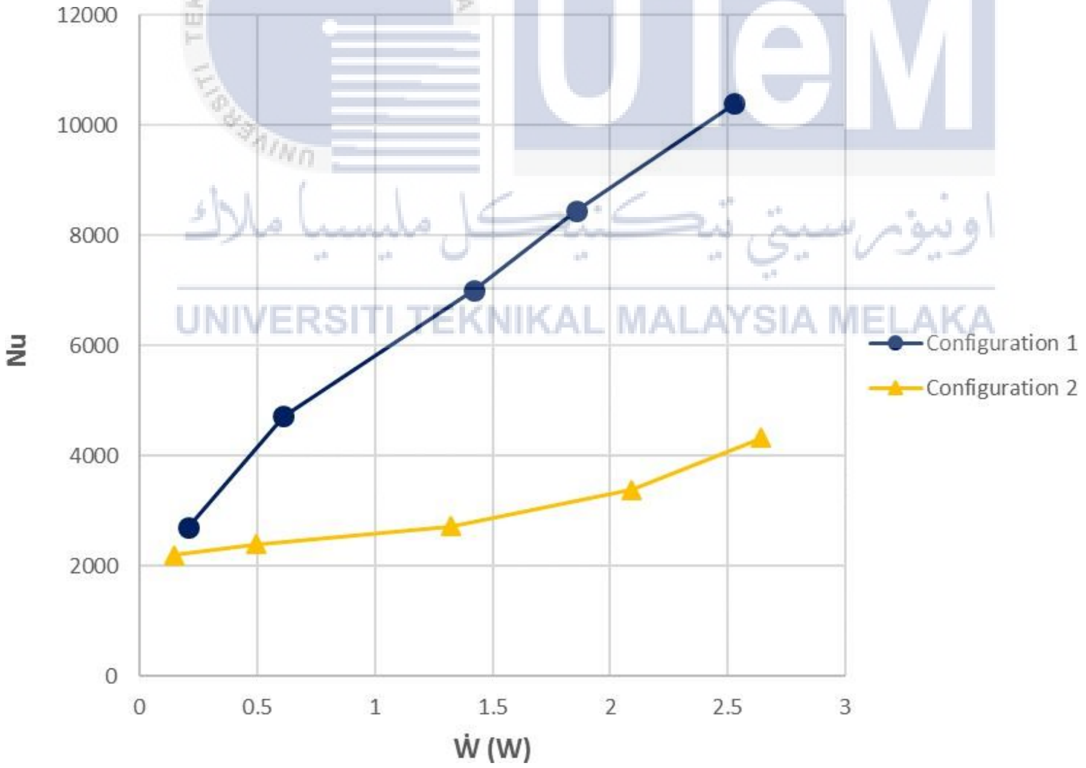

Figure 4.6: Plot of the Nusselt number, Nu against the corresponding required pumping power, Ẇ (W) for both configuration of the compact finned copper foam heat exchangers.

In order for convenient comparison of the results obtained with open literature, the dimensionless pump power, C_fRe^3 which is a combination of the pressure drop and Reynolds number as expressed in equation (8) is used. (Wang, Kong, Xu, & Wu, 2019)

$$C_fRe^3 = \frac{\Delta P.Re^3}{0.5.\rho.V^2} \tag{8}$$

ΔP is the pressure drop (Pa) across the heat exchanger measured by differentiating the pressure of the cooling fluid near the inlet of the test section with the pressure near the outlet of the test section. ρ is the density of the cooling fluid (kg/m^3), Re is the Reynolds number of the cooling fluid and V is the average velocity of the cooling fluid in the test section (m/s).

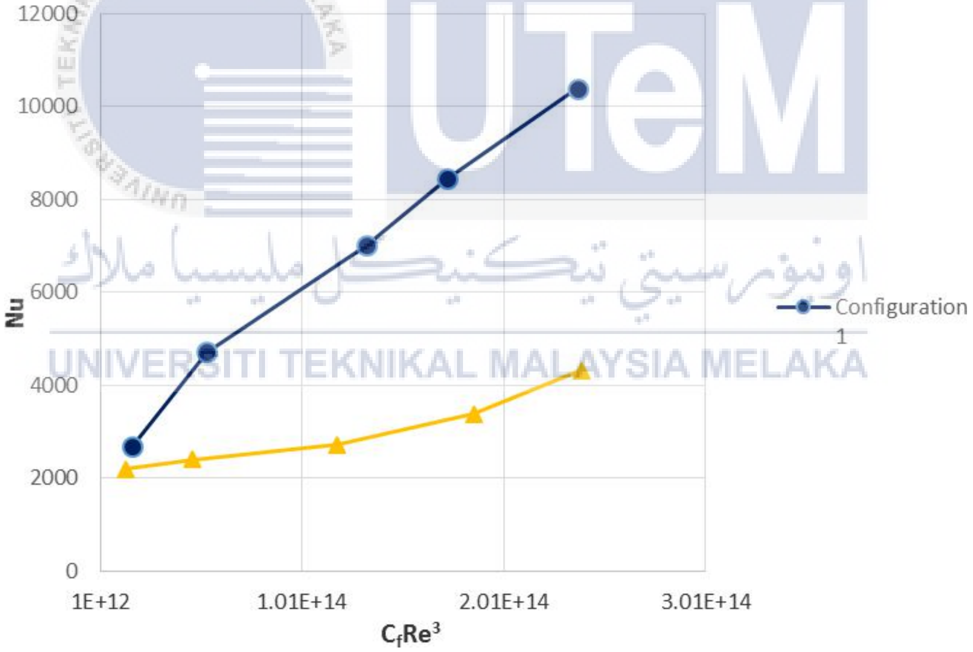

Figure 4.7: Plot of the Nusselt number, Nu against the corresponding dimensionless pump power, CfRe3 for both configuration of the compact finned copper foam heat exchangers.

At a fixed pumping power condition, the thermal performance of configuration 1 of the compact finned copper foam heat exchanger is better than that of configuration 2. At a fixed lower pumping power situation, configuration 1 heats up 1.2 times faster than configuration 2, while at a fixed higher pumping power condition, it heats up 2.5 times faster. Despite the fact that configuration 1 consumes more pump power due to its larger pressure drop, its substantially better thermal performance at the same Reynolds number greatly outperforms configuration 2, allowing for better heat transfer at the same pumping power situation for configuration 1.

4.3.1 Comparison with Open Literature

The results of the current study are compared to the available literature to check if they agree with those of prior similar investigations. Due to their similarities in finned metal foam heat exchanger design to that of configuration 1, the Nusselt and dimensionless pump power numbers are acquired from (Wang, Kong, Xu, & Wu, 2019) and compared with the current study.

Table 4.3.1.1: Details of the heat exchanger in open literature used for comparison.

	Present Study	Wang 1	Wang 2
Thickness (mm)	20	15	15
Material	99.99% Copper Alloy	Copper alloy	Copper alloy
Pore Density (PPI)	60	20	30
Porosity	0.93	0.92	0.91

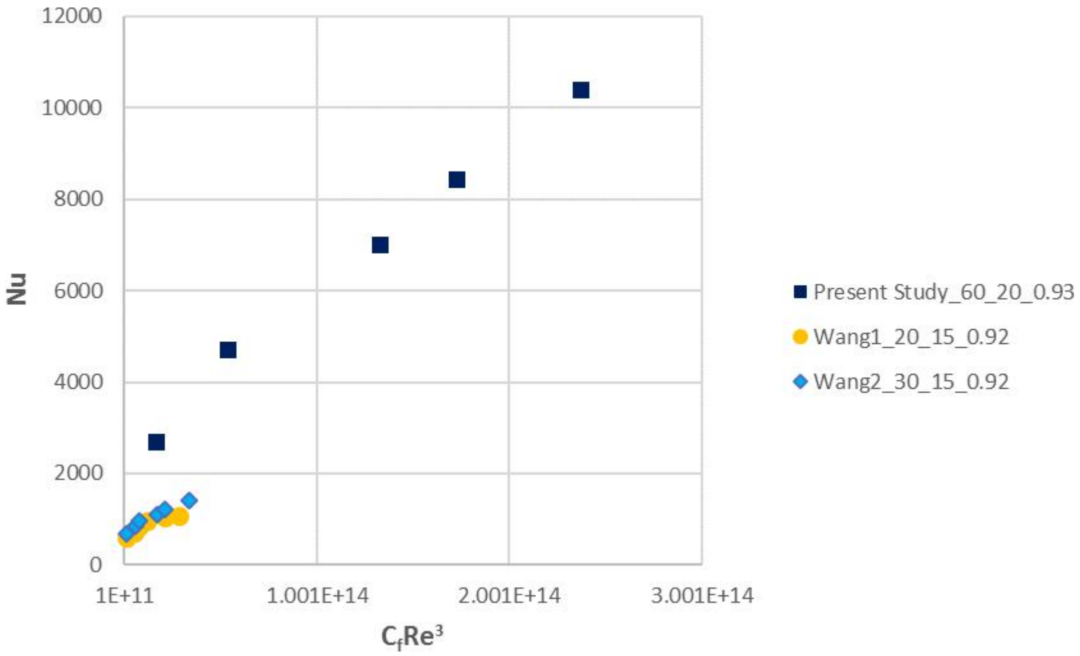

Figure 4.8: Comparison of Nusselt number, Nu against dimensionless pump power, CfRe3 from present study with open literature (Wang 1 and Wang 2 are data reported by Wang, Kong, Xu, and Wu (2019))

The legends in figure are represented as 1_2_3_4, where ‘1’ is the study reference, ‘2’ is the pore density, ‘3’ is the foam thickness and ‘4’ is the foam porosity. The Nusselt number from the open literature are lower than the values in the present study for same pumping power condition due to their lower pore density. The Nusselt number of the present study is larger compared to that of the 30 PPI copper foam heat exchanger from previous study with almost similar thickness and porosity albeit a larger difference when compared with the difference between the 20 PPI and 30 PPI copper foam heat exchanger due to the lower pressure drop measured in the present study.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Using forced convection, an experimental examination of the performance of compact finned copper foam heat exchangers with various designs in a horizontal channel was carried out. The tiny finned heat exchanger was made up of 99.99 percent copper alloy foam with a pore density of 60 PPI and a porosity of 0.93 in both configurations. Only the Reynolds number and the configuration of the compact finned copper foam heat exchanger were changed in this study, which ranged from 9217 to 35517. The following conclusions were drawn from the research.

For starters, due to the larger heat transfer area in configuration 1, the thermal performance of the compact finned copper foam heat exchanger for configuration 1 is 2.5 to 5 times better than that of configuration 2 at a fixed flow, with the better thermal performance for configuration 1 becoming more pronounced at higher cooling fluid flow rates. Furthermore, when compared to configuration 2, the pressure drop across the tiny finned copper foam heat exchanger for configuration 1 is 5 times higher. This is due to the presence of air spaces between finned copper foams in configuration 2, which allows the cooling fluid to flow more freely. Finally, when considering pump power consumption, the compact finned copper foam heat exchanger configuration 1 has nearly 1.2 to 2.5 times greater thermal performance than the configuration 2. Despite the increased pressure drop for configuration 1, the thermal performance is much better due to the fact that configuration 1 has twice the heat exchange surface.

In conclusion, the finned copper foam's various configurations have a significant impact on its thermal and hydraulic performance. Based on the flow uniformity analysis performed in the test part of the test rig as well as a comparison of experimental results with open literature, the test rig and testing process appear to be satisfactory.

In the future, it would be useful to pursue designing compact finned metal foam heat exchangers with various configurations, such as louvred fin designs, in order to achieve the best thermal and hydraulic performance. It would also be interesting to investigate how the thermal interface material between the metal foam fins and the aluminium fins affects the heat exchanger's thermal performance.

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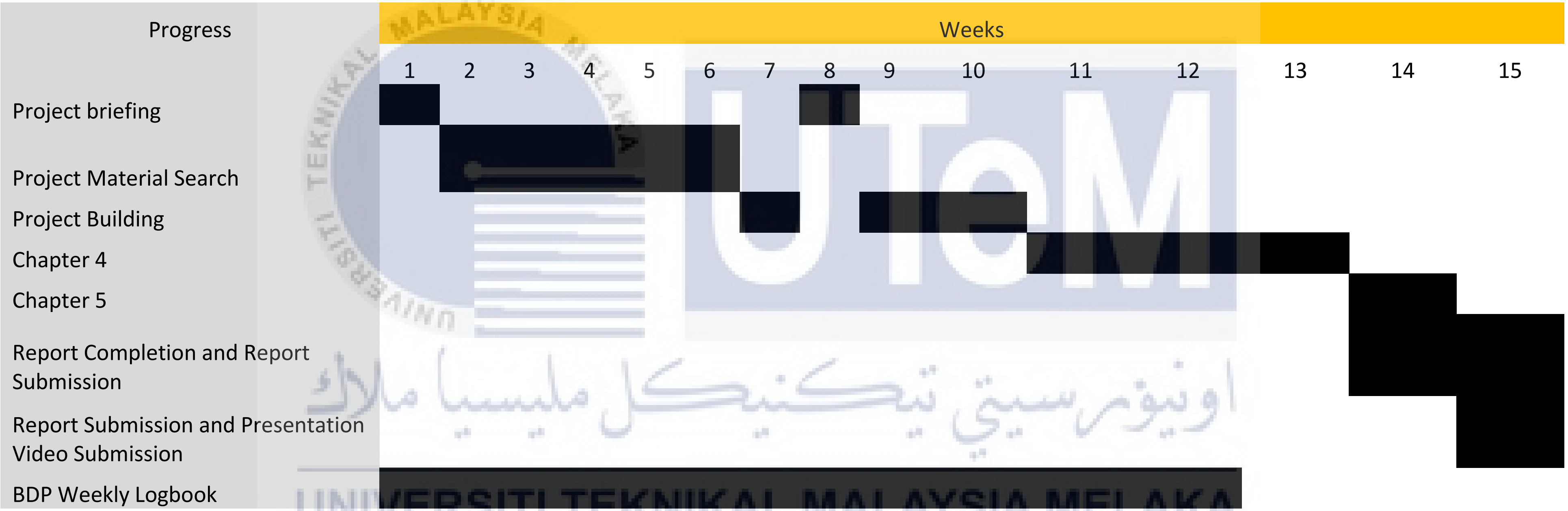
APPENDICES

APPENDIX A BDP 2 Gantt Chart.



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