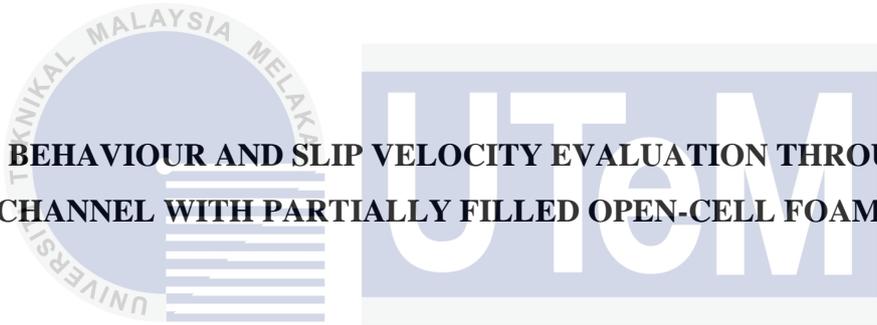




Faculty of Mechanical Technology and Engineering



**FLOW BEHAVIOUR AND SLIP VELOCITY EVALUATION THROUGH A
CHANNEL WITH PARTIALLY FILLED OPEN-CELL FOAM**

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Khairul Azhar Bin Mustapha
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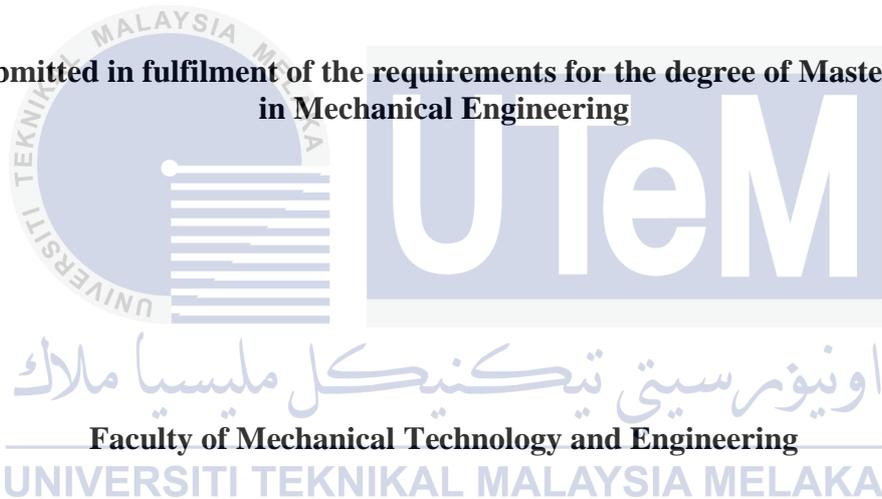
Master of Science in Mechanical Engineering

2024

**FLOW BEHAVIOUR AND SLIP VELOCITY EVALUATION THROUGH A
CHANNEL WITH PARTIALLY FILLED OPEN-CELL FOAM**

Khairul Azhar Bin Mustapha

**A thesis submitted in fulfilment of the requirements for the degree of Master of Science
in Mechanical Engineering**



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DECLARATION

I hereby declare that this thesis entitled “Flow Behaviour and Slip Velocity Evaluation Through a Channel with Partially Filled Open-Cell Foam” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:
Name	:	Khairul Azhar Bin Mustapha.....
Date	:	11 September 2024.....



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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature :

Supervisor Name : Dr. Fadhilah Binti Shikh Anuar

Date : 11 September 2024



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DEDICATION

To my beloved mother and father and to the people that still finding their inner satisfying.



ABSTRACT

An open-cell metal foam (OCMF) is a porous structure material that is widely known among researchers and industries for its many benefits, such as its lightweight, low density, good impact absorption, and ability to transfer heat within its porous structure. However, using the foam in a fully filled configuration results in a high pressure drop, suggesting the need for a partially filled configuration. Hence, an interface condition between the clear and porous regions of the partially filled configuration must be well-understood to take advantage of its porous structure. This research aims to investigate fluid flow characteristics in the partially filled configuration, leading to the development of a slip velocity model for the OCMF. The foams used in the experiments were produced using an additive manufacturing method, where the images of 5 PPI (pores per inch) OCMF structures were used as a base structure in manipulating various pore diameters and porosities. The fluid flow characteristics across the 3D printed foams were investigated experimentally using a hot-wire anemometer and Computational Fluid Dynamics (CFD) simulation in Ansys Fluent Software. This study configured the porous structure of open-cell foam in two-dimensional (2D) simulation, since it is easier to be completed with less computational cost and the channel setup with a foam block can be considered symmetrical due to its rectangular design. Additionally, this study focused on obtaining averaging data in the free stream region to understand the effects of foam properties in the partially filled configuration. Based on the experimental data, the slip velocity model was developed using dimensional and regression analyses. Results show that the fluid flow behaviours in the partially filled channel would be affected by the presence of the foam, especially in the downstream region, where the velocity fluctuates and larger at the interface and clear regions. The foam size, pore diameter and blockage ratio are the significant factors that influence the flow behaviours in the partially filled channel. The pressure drop also varies from 343.53 - 1818.26 Pa/m at an inlet velocity of 5.0 m/s. Meanwhile, the slip velocity obtained from the proposed model is within the measurement uncertainties of the experimental studies. The slip velocity model that used an averaging value slightly underpredicted the real phenomenon at the interface region with a maximum percentage difference is 0.13 %. The secondary flow from the porous region caused a fluctuation of slip velocities and the values were higher than the inlet velocity.

PENILAIAN TINGKAH LAKU ALIRAN DAN HALAJU GELINCIR MELALUI SALURAN SEPARA TERISI BUSA SEL TERBUKA

ABSTRAK

Busa logam sel terbuka adalah satu struktur berliang yg sangat terkenal di kalangan penyelidik and pengamal industri disebabkan kelebihanannya seperti bersifat ringan, ketumpatan yang rendah, penyerapan hentaman yang baik serta keupayaannya untuk mengalirkan haba melalui struktur berliang. Walau bagaimanapun, penggunaan busa secara pengisian penuh dalam satu saluran bendalir menyebabkan susutan tekanan yang tinggi, di mana, pengisian separuh busa logam sel terbuka disarankan bagi mengurangkan susutan tekanan tersebut. Oleh itu, keadaan antara dua kawasan, iaitu di antara kawasan yang berliang dan tidak berliang pada sistem saluran pengisian separuh ini perlu difahami dengan baik bagi memanfaatkan struktur berliang dalam saluran tersebut. Penyelidikan ini bertujuan untuk mengkaji sifat bendalir di dalam sistem saluran pengisian separuh dan menghasilkan satu model halaju gelincir untuk busa logam sel terbuka. Dalam kajian ini, busa sel terbuka dihasilkan menggunakan kaedah teknologi pembuatan aditif di mana gambar struktur asal busa logam 5 PPI (5 liang per inci) digunakan sebagai satu struktur asas dalam memanipulasikan pelbagai saiz diameter leliang dan keliangan. Sifat aliran bendalir melalui busa-busa tersebut telah dikaji dengan menggunakan anemometer dawai panas dan simulasi Pengkomputeran Dinamik Bendalir (CFD) menggunakan perisian "Ansys Fluent". Kajian ini mengkonfigurasi struktur berliang busa sel terbuka di dalam simulasi dua dimensi (2D), kerana ianya lebih mudah diselesaikan secara pengkomputeran dan saluran bersama blok busa tersebut boleh dianggap simetri berdasarkan bentuk segi empat tepatnya. Fokus kajian ini adalah untuk mendapatkan data purata bagi aliran dalam kawasan yang kosong di mana kawasan tersebut mungkin dipengaruhi oleh sifat busa yang terletak berhampiran dan memenuhi sebahagian saluran tersebut. Menggunakan data eksperimen, model halaju gelincir telah dihasilkan melalui analisis dimensi dan regresi. Hasil kajian menunjukkan dengan adanya busa sel terbuka dalam saluran, ia menyebabkan perubahan pada aliran bendalir terutamanya pada kawasan hilir, dengan nilai halaju tidak tetap di kawasan antara muka serta menjadi lebih laju di kawasan tidak berliang. Saiz busa, diameter leliang dan nisbah halangan adalah faktor penting yang mempengaruhi aliran bendalir di dalam sistem saluran pengisian separuh. Susutan tekanan juga berlaku, di mana jumlah susutan adalah dalam lingkungan 343.53 - 1818.26 Pa/m pada halaju masuk 5.0 m/s. Manakala, model halaju gelincir yang yang dicadangkan berada dalam ketakpastian pengukuran halaju gelincir yang diperolehi daripada eksperimen. Model halaju gelincir ini menggunakan nilai purata dari pelbagai parameter, dimana ia menghasilkan nilai yang sedikit rendah berbanding keadaan sebenar yang berlaku pada antara muka kawasan berliang dengan peratusan perbezaan tertinggi adalah sebanyak 0.13 %. Kehadiran aliran sukender pada antara muka kawasan berliang telah menyebabkan nilai halaju gelincir berubah-ubah dan ianya adalah lebih tinggi daripada halaju masuk.

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TABLE OF CONTENT

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENT	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF APPENDICES	x
LIST OF ABBREVIATIONS AND SYMBOLS	xi
LIST OF PUBLICATIONS	xiii
CHAPTER	
1. INTRODUCTION	1
1.1 Background of study	1
1.2 Problem of statement	3
1.3 Objectives of study	5
1.4 Scope of study	5
1.5 Thesis structures	6
2. LITERATURE REVIEW	8
2.1 Overview	8
2.2 Open-cell metal foam and 3D printed foam production	8
2.2.1 Background of open-cell metal foam	8
2.2.2 Production of 3D printed open-cell foam using reverse engineering method	12
2.3 Classical theories on fluid flow in porous media	18
2.3.1 Darcy law	19
2.3.2 Forchheimer law	21
2.3.3 Ergun law	22
2.4 Fluid flow behaviours across open-cell foam	23
2.4.1 Fluid Flow behaviours in partially filled configuration	23
2.4.2 Slip velocity at the interface of porous-clear region	25
2.4.3 Pressure drops effects	31
2.5 Numerical studies on porous media and 3D printed open-cell foam	34
2.6 Summary	39
3. METHODOLOGY	40
3.1 Overview	40
3.2 Production of 3D printed open-cell foam and physical properties determination	42

3.2.1	Dimension reconstruction on open-cell metal foam	42
3.2.2	Three-dimensional (3D) printing technologies	46
3.2.3	Surface topology and roughness test of 3D printed open-cell foam	50
3.2.4	Determination of open-cell foam properties	51
3.3	Experimental setup and calibration	53
3.3.1	Test rig	54
3.3.2	Experimental setup	56
3.3.3	Instruments calibration and validation	58
3.3.4	Uncertainty calculation for experimental works	60
3.4	Regression analysis and model validation	61
3.4.1	Parameter selection	61
3.4.2	Dimensional analysis of slip velocity	63
3.5	Numerical studies on fluid flow behaviours	66
3.5.1	Computational Fluid Dynamics (CFD) model construction	67
3.5.2	Grid independence test for the channel and porous medium	69
3.5.3	Cell zone and boundary condition	71
3.5.4	Solving and visualization	72
3.5.5	Model validation	73
3.6	Summary	76
4.	RESULT AND DISCUSSION	77
4.1	Overview	77
4.2	Microstructural and physical properties of 3D printed open-cell foam	77
4.2.1	Physical and microstructural properties	77
4.2.2	Morphologies and surface roughness	80
4.2.3	Permeability of various foams	86
4.3	Flow characteristics in partially filled channel with open-cell foam	90
4.3.1	Velocity profiles	91
4.3.2	Pressure drops effects	102
4.4	Regression analysis and slip velocity	106
4.5	Fluid flow simulation	109
4.5.1	Flow behaviours across partially filled channel	109
4.5.2	Slip velocity at the middle of partially filled channel	120
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	125
5.1	Conclusion	125
5.2	Recommendations for future research	126
	REFERENCES	128
	APPENDICES	143

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Common print materials for FDM and SLS (Kafle et al., 2021)	16
3.1	Dimension of 3D printed open-cell foams	46
3.2	Properties of 3D printing materials	49
3.3	Physical properties of open-cell metal foam	50
3.4	Dimensional matrix for independent and dependent parameters	64
3.5	Dimensionless π groups	66
3.6	Dimensions of the channel and porous medium	69
3.7	Parameters of grid independence test for 2 scale foam	71
3.8	Parameter and boundary conditions for channel and porous medium	72
4.1	Permeability and inertial coefficient for fully developed configuration	88
4.2	Physical properties of 3D printed open-cell foam	88

اونيورسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Example of microstructure image of open-cell metal foam for different pore densities: (a) 10 PPI and (b) 30 PPI (Shikh Anuar et al., 2018)	9
2.2	Foam structure with different printing technologies and materials (Wang et al., 2020): (a) SLS, (b) Jet Fusion and (c) FDM	17
2.3	Types of flow (Dou, 2005)	19
2.4	Partially filled circular pipe from two different studies: (a) Qu, Xu, and Tao (2012) and (b) Xu and Gong (2018)	24
2.5	(a) Slip velocity (Beavers and Joseph, 1967) and (b) Flow discontinuity at the interface region (Ochoa-tapia and Whitaker, 1995)	28
2.6	The flow behaviours across open-cell metal foam (Shikh Anuar, Ashtiani Abdi, and Hooman, 2018)	29
2.7	Pressure field from CFD simulation by (Tang, Wang, and Huang, 2023); (a) $U_{inlet} = 10$ m/s and (b) $U_{inlet} = 80$ m/s	33
2.8	Schematic diagram of computational domain with REV of porous metal (Park, Seo, and Jeong, 2020).	35
2.9	Computational domain and cross-section of velocity distributions (Yu et al., 2021)	37
2.10	Schematic computational domain and velocity contour (Sauret, Hooman, and Saha, 2014)	38
3.1	Flow chart of methodology	41
3.2	5 PPI open-cell metal foam: (a) CT scan image translation and (b) original microstructure	43
3.3	3D printed open-cell foam: (a) CAD drawing 2 scale foam and (b) microstructure of the open-cell foam	43
3.4	Comparison of 3D printed open-cell foam (a) Original size 5 PPI and (b) 2 scale	45
3.5	(a) Base area of channel, and (b) Partially filled configuration	45
3.6	(a) FDM processing, (b) SLS printers, (c) SLS pre-processing and (d) SLS post-processing	48
3.7	(a) Image captured by microscope and (b) Processed image for surface roughness test	51
3.8	Schematic diagram of close-loop wind tunnel	54
3.9	Schematic diagram of channel with measurement points	57
3.10	Acrylic solid block setup in the channel	57
3.11	Velocity profiles in the unloaded channel with different frequencies	59

3.12	Pressure gradient for unloaded channel and loaded channel with solid block	60
3.13	Channel setup with different blockage ratios: (a) 0.3, (b) 0.6, and (c) 0.9	68
3.14	Meshing of 2 scale foam with different grid independence test: (a) Test 1, (b) Test 2 and (c) Test 3	70
3.15	Area of observation in CFD simulation	73
3.16	CFD model validation	75
4.1	(a) SLS, 5 PPI, (b) SLS, 2 scale foam, (c) SLS, 4 scale foam, (d) SLS, 6 scale foam, and (e) FDM, 6 scale foam	78
4.2	(a) SLS foam ligament (b) Cut-section of the SLS foam, (c) FDM ligament (d) Residues within FDM foam structure (e) Microstructure of 30 PPI open-cell metal foam and (f) Microstructure of 10 PPI	80
4.3	Image processing using Image J: (a) Raw images of SLS's foam, (b) SLS's subtracted background image, (c) Raw images of FDM's foam, and (b) FDM's subtracted background image	81
4.4	Surface plot for SLS foam: (a) Top, (b) Side 1, and (c) Side 2	82
4.5	Surface plot for FDM foam: (a) Top, (b) Side 1, and (c) Side 2	83
4.6	Comparison between faces (frontal area): (a) SLS foam and (b) FDM foam	85
4.7	Comparison of surface roughness between SLS and FDM foams	86
4.8	Determination of Forchheimer's coefficient for different scaling factors; (a) 2 scale, (b) 4 scale and (c) 6 scale	87
4.9	Plot of permeability against foam height	89
4.10	Plot of inertial coefficient against a ratio of pore diameter and foam height	90
4.11	Velocity profiles in the upstream region with different blockage ratios: (a) 0.3, (b) 0.6, and (c) 0.9	92
4.12	Velocity profiles in downstream region with different blockage ratios: (a) 0.3, (b) 0.6, and (c) 0.9	94
4.13	Velocity profiles at middle region with different blockage ratios: (a) 0.3, (b) 0.6, and (c) 0.9	96
4.14	Comparison of velocity profiles between 3D printed foams and acrylic blocks with different blockage ratios: (a)-(b) 0.3 and (c)-(d) 0.6	99
4.15	Velocity profiles across the open-cell metal foam at three different regions: (a) Upstream, (b) Downstream, and (c) Middle	101
4.16	Comparison of pressure drops between 3D printed foam and acrylic block	103
4.17	Pressure drops of 3D printed open-cell foam with various pore diameters and blockage ratios	104
4.18	Comparison of pressure drops between 3D printed foams and open-cell metal foam	106
4.19	Experimental against predicted slip velocity U_s/U_{inlet} of 3D printed foam	107
4.20	Comparison of dimensionless slip velocity against pore diameter between experimental data, predicted model and existing literature	109

4.21	Velocity streamlines for blockage ratio of 0.3 at different inlet velocities and pore diameters	113
4.22	Velocity streamlines for blockage ratio of 0.6 at different inlet velocities and pore diameters	116
4.23	Velocity streamlines of blockage ratio 0.9 at different inlet velocities and pore diameters	119
4.24	Comparison of velocity profiles between CFD analysis and experimental data at the middle of partially filled channel	122
4.25	Comparison of slip velocity at the interface of porous-clear region between CFD analysis, experimental values and predicted model at different velocities: (a) 1.0 m/s, (b) 3.0 m/s, (c) 5.0 m/s and (d) 1.0 – 5.0 m/s	124



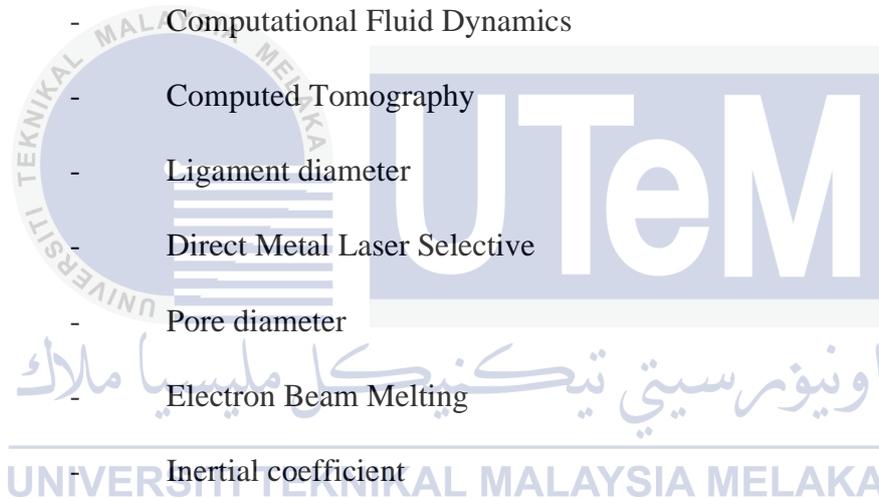
LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Example Calculation (Dimensional Analysis)	143
B	Pressure Drop Result (3D printed foam)	144
C	Velocity Result (3D printed foam)	145
D	Pressure Drop Result (Conventional metal foam)	146
E	Velocity Result (Conventional metal foam)	146



LIST OF ABBREVIATIONS AND SYMBOLS

3D	-	Three Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AM	-	Additive Manufacturing
CAD	-	Computed Aided Design
CFD	-	Computational Fluid Dynamics
CT	-	Computed Tomography
d_l	-	Ligament diameter
DMLS	-	Direct Metal Laser Selective
d_p	-	Pore diameter
EBM	-	Electron Beam Melting
f	-	Inertial coefficient
FDM	-	Fused Deposition Modeling
FFF	-	Fused Filament Fabrication
h	-	Measured height
h_f	-	Foam height
h_c	-	Channel height
IR 4.0	-	Fourth Industrial Revolution
K	-	Permeability
l_f	-	Foam length
OCMF	-	Open-Cell Metal Foam



PA	-	Polyamide / Nylon
PLA	-	Polylactic acid
PPI	-	Pore Per Inches
SLA	-	Stereolithography
SLS	-	Selective Laser Sintering
SLM	-	Selective Laser Melting
U	-	Measured velocity
U_m	-	Mean pore velocity
U_s	-	Slip velocity
U_{inlet}	-	Inlet velocity
U_0	-	Original velocity in unloaded wind tunnel
U_m	-	Mean pore velocity
UV	-	Ultraviolet
V_{void}	-	Void volume
V_{total}	-	Total volume (full solid)
$\Delta P/\Delta l$	-	Pressure drops per unit length
ε	-	Porosity
μ	-	dynamic viscosity
μ_{fluid}	-	Fluid viscosity
ρ_{fluid}	-	Fluid density
$1/\alpha$	-	Viscous Coefficient

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Open-cell metal foam is a kind of porous media with a unique structure made of a solid matrix with interconnected pores. The open-cell metal foam is promising for wide applications due to its high strength, low density, good impact absorption, and its ability to move heat within its porous structure. The open-cell metal foam also has high porosity, commonly more than 90%, thus providing a large specific surface area and allowing the process of fluid mixing (Anuar, Malayeri, and Hooman, 2017). Due to its porous structure, naturally, the OCMF offers two different modes of heat transfer, (1) conduction which depends on the type of material used, and (2) convective heat transfer because of its pass-through structure. In other applications, OCMF has gained interest among researchers and industries over the years such as sound absorbers (Wan et al., 2021), dampers, filters (Mehrzi and Ravari, 2019) and in fuel cells as coolant distributors (Tan et al., 2018; Vazifeshenas, Sedighi, and Shakeri, 2020). In heat exchanger applications, normally the OCMF is used in HVAC&R, electronics cooling and solar thermal plants (Kuruneru et al., 2020).

In current practice, the open-cell metal foam can be manufactured utilizing several procedures such as direct foaming of melts, solid-gas eutectic solidification, and investment casting. In IR 4.0 era, an additive technology could be used to manufacture porous structures using either metallic or non-metallic materials. However, the usage of non-metallic material may restrict its potential in the thermal application. Nevertheless, the complicated structure

of the porous foam in a pipe or channel may create a disturbance to the fluid flow, allowing a better fluid mixing for a higher heat transfer process. One major drawback of open-cell metal foam due to its complicated structure is a massive pressure drop. Alternatively, the OCMF can be arranged to partially fill a part of a tube or channel, instead of fully-filled the configurations. However, the partially filled configuration that contains a porous region and a non-porous region may induce a slip condition at the interface. Thus, the fluid behaviours and slip conditions must be well-understood to make use of the complicated structure of the open-cell foam. There are certain debates on slip and no-slip conditions at an interface region between porous and non-porous (free stream) regions. The most popular theory, Darcy law deduces there should be a statistical average of the slip velocity value immediately outside the porous block (Beaver and Joseph, 1967). Therefore, Beavers-Joseph (1967) proposed the presence of the slip condition at the interface region. Researchers also started to investigate the slip condition using extended models from either the Darcy or Beaver-Joseph models to describe flow in open-cell foam. However, a recent experimental study on OCMF by Shikh Anuar, Ashtiani and Hooman (2018) found a noteworthy outgoing flow from the porous into the free stream regions in a vertical direction through the interface, and there exist no-flow regions in certain areas of the porous structure. Thus, the effects of this secondary flow (a flow that comes out vertically from the porous structure to the free stream region through the interface region) at the interface region is still debated due to the presence of slip velocity and non-slip condition, contributed by its pore-ligament constructions. Moreover, the exposed structure next to a clear region is a surface with the ligament structure spikes and randomly distributed the small pores. The characteristic of another secondary flow, which is formed inside the porous region also remains unclear (Kim et al., 2021).

In this research, a reverse engineering technique is proposed to investigate the flow behaviours across a partially filled channel with open-cell foam. The exact structure of the

original open-cell metal foam was produced by using additive manufacturing (AM) methods, where the pore diameter was enlarged to the desired size so that velocities in the partially filled channel, including pore velocity (velocity in the porous structure) can be experimentally measured using a hot-wire anemometer. A morphology test was conducted in choosing a better 3D printing method to minimize the frictional effects on the fluid flow behaviours. This research also proposes an open-cell metal foam slip velocity model through dimensional and regression analyses and gaining insights of what happened in the partially filled configuration by focusing more on the effects of open-cell foam with various heights and pore sizes.

1.2 Problem of statement

An OCMF is very valuable since it is used in a very wide range of applications (Mehrizi and Ravari, 2019; Vazifeshenas, Sedighi, and Shakeri, 2020) where it is typically produced using different types of conventional method (Banhart, 2000; Husain, Siddiquee, and Khan, 2022). The conventional method is seen to be very complicated and high in cost (Wan et al., 2021). For instance, an investment casting is a common method to produce OCMF where it may take a few steps to finalize the end product (Sutygina et al., 2020). However, with the introduction of the AM method, like 3D printing, (Zhang et al., 2022; Gama, Ferreira, and Barros-Timmons, 2019; Kim et al., 2021; Zhou et al., 2022; Wang et al., 2020) the open-cell foams have been successfully produced in a simpler method.

The fully filled configuration with open-cell metal foam has always been proposed in many applications but there is a constraint in pressure drop, in which the intricate structure of metal foam contributes to high pressure drop (Khadhrawi et al., 2020; Jadhav et al., 2022). Normally, the corresponding pressure drop in the fully filled configuration is considerably high which may generally about three to four folds of magnitude higher compared to an

empty channel due to its complex structure (Qu, Xu, and Tao., 2012). At the same time, the pressure drop causes a reduction in the performance efficiency of the system (Zargartalebi and Azaiez, 2019) and the fluid also needs more pumping power to compensate the pressure drop (Lu, Zhang, and Yang, 2016). Thus, many studies have considered a partially filled configuration (Lu, Zhang, and Yang, 2016; Sener and Yataganbaba, 2016; Xu et al., 2018) to lessen the impact of pressure drop. However, the partially filled configuration with open-cell foam needs further study to understand the effects on the flow behaviours and pressure drop, especially with the presence of an interface region between the clear (non-porous region) and the porous region (Shikh et al., 2018). The OCMF studies usually adapted the general classical equation of porous media for different types of porous media such as bed rocks, and sands (Alvandifar and Amani, 2018). However, the well-known classical macroscopic models such as Beaver and Joseph (1967) and Kuznetsov (1996) could not accurately describe the real flow behaviours at the interface of OCMF (Anuar, Malayeri, and Hooman, 2017; Sauret, Abdi, and Hooman, 2014) and the findings contributed to additional modified models based on the Beaver-Joseph model. A lot of numerical studies (Yerramalle, Premachandran, and Talukdar, 2020; Kotresha and Gnanasekaran, 2020; Xu and Gong, 2018; Khadhrawi et al., 2020) and analytical studies (Mahmoudi, Karimi, and Mazaheri, 2014; Xu et al., 2018; Li and Hu, 2019) have been conducted on the partially filled configuration with porous medium. However, an intricate flow phenomenon at the interface region, including the slip velocity could not be accurately explained using a continuity equation since more experimental studies are required to address the real phenomenon occurs in that region (Nair and Sameen, 2015). The underlying theory on the interface condition, specifically for the open-cell metal foam should be investigated and validated by experiments. There are limited experimental works with open-cell metal foams that discussed the interface conditions, due to expensive foam samples, tedious, and time-consuming work. Nevertheless, additional

experimental works are required to obtain accurate information in describing the flow behaviours and slip velocity at the interface of foam-fluid regions, and understanding the pressure drop effects.

1.3 Objectives of study

The main objectives of this research are:

1. To produce 3D printed open-cell foams based on a conventional open-cell metal foam structure.
2. To investigate flow characteristics patterns across a partially filled channel with open-cell foams.
3. To propose a predicted model for slip velocity at the interface of the metal foam-fluid region by correlating the flow characteristics with foam geometrical properties.

1.4 Scope of study

The scopes in this research are:

- a) Three Dimensional (3D) printed open-cell foam structure is redesigned from the original 5 PPI open-cell metal foam, where the pore diameters are manipulated. Normally, the open-cell metal is classified based on pore density such as 5 PPI, 10 PPI, 30 PPI etc. This study used 5 PPI as a benchmark to produce 3D printed open-cell foam.
- b) The 3D printed open-cell foams are manufactured using two types of AM technologies and morphology tests are conducted to select the best technology to produce the open-cell foams.

- c) This research focuses on the effects of pore diameter and foam height on the flow behaviours and slip velocity in a partially filled channel. The flow inside the porous and non-porous regions is investigated experimentally and numerically.
- d) This research will develop a slip velocity model from the 3D printed foam data that is applicable for 5 PPI open-cell foam and smaller pore diameters.
- e) The effect of pressure drops due to the manipulating parameters e.g., the foam geometrical properties are also investigated as a part of this research, expecting their influences on the flow behaviours in the partially channel.
- f) The numerical study is based on a two-dimensional model using the existing porous model in Ansys Fluent software and is compared to the results of the predicted model and experiments using the open-cell foams.

1.5 Thesis structure

This thesis structured in five chapters consists of an introduction, literature review, methodology, results and discussions, and also a conclusion and recommendations.

Chapter 1 - Introduction

This chapter describes the basis of this research that is relatable to the uses of open-cell metal foam in a partially filled configuration. A brief background of the research is presented along with the problem statement and the objectives of this research in giving the novelty and the purposes of this research. The scope of the study has also been outlined to illustrate the boundaries of this research.

Chapter 2 – Literature Study

A review of the previously published works is conducted to have more understanding of all aspects of the research and used as a guideline for achieving better results. It concludes