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

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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	:	....
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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	:	....
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Date	:	11 September 2024

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 kelebihannya 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 mengunakan 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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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

LIST OF PUBLICATIONS

1. Shikh Anuar, F., Mustapha, K. A., Mohd Sa’at, F. A. Z., Zini, N. H. M., Mat Tokit, E., Satishwara Rao, N., Hooman, K., and Abdi, I. A., 2023. Microstructural properties and surface roughness of 3D printed open cell-foam. *Jurnal Tribologi*.

2. Mustapha, K. A., and Anuar, F. S., 2022. Prediction of Slip Velocity at the Interface of Open-Cell Metal Foam Using 3D printed Foams. *Colloids and Interfaces*.

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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 (Mehrizi 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 slips 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