NUMERICAL STUDY ON A PARTIALLY FILLED CHANNEL WITH OPEN-CELL METAL FOAM

SATISHWARA RAO S/O NARASIMMANAIDU

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

NUMERICAL STUDY ON A PARTIALLY FILLED CHANNEL WITH OPEN-CELL METAL FOAM

SATISHWARA RAO S/O NARASIMMANAIDU

A report submitted
in fulfilment of the requirements for the Degree of
Bachelor of Mechanical Engineering (Thermal Fluids)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2020

`

DECLARATION

I declare that this project entitled “Numerical study on a Partially Filled Channel with Open-cell Metal Foam” is the result of my own work except as cited in the references.

Signature : ....

Name : SATISHWARA RAO A/L NARASIMMANAIDU

Date : 24 JUNE 2020

`

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Thermal Fluids).

Signature : ....

Name of Supervisor : DR. FADHILAH BINTI SHIKH ANUAR

Date : 24 JUNE 2020

`

DEDICATION

To my beloved father, mother and siblings for the endless support

`

ABSTRACT

A metal foam is widely used in automotive, furniture, and construction industry. Metal foam has excellent fire penetration, thermal insulation and sound absorption properties. In this study, partially filled channel with metal foam is investigated as a replacement to a fully filled channel that causes a massive pressure drop effects. The interface of the porous medium has to be identified and remodelled to simulate the exact airflow in metal foam because of the metal foam complex interior. The objectives of this project are to model a partially filled channel with a porous medium and also to investigate the fluid flow behaviour and pressure drop in a partially filled channel. Different pore density of the open-cell aluminium foam block, 5, 10 and 30 pores per inch (PPI) foam is considered, including various foam thickness and inlet velocity. The Computational Fluid Dynamics (CFD) is conducted to extend the results of past literature to obtain accurate data. The Ergun-Forcheimmer's equation is used to define the viscous and inertial resistance in the porous medium domain while the Navier-Stokes equation was used for the clear region. Two-dimensional (2D) channel configuration is developed because of its symmetrical model. A validation with 20 PPI porous medium from other literature was made. The results are acceptable. From the simulations, the velocity distribution in the channel was examined particularly at the fluid flow behaviour at upstream, partially filled and downstream sections. The pressure drop was discussed in detail by observing the contours. Comparison of velocity and pressure gradient between experimental and simulation data are also shown in the form of a graph including the in agreement results of past literature. Thus, the flows behaviour at the upstream and downstream region were also explained which are relevant to this project.

`

ABSTRAK

Busa logam banyak digunakan dalam industri automotif, perabot, dan pembinaan. Logam berliang ini mempunyai sifat penembusan api, penebat haba dan penyerapan bunyi yang sangat baik. Dalam kajian ini, saluran yang diisi sebahagiannya dengan busa logam telah dipertimbangkan sebagai pengganti saluran penuh busa logam yang menyebabkan kesan penurunan tekanan yang besar. Muka medium berliang yang seusai harus dikenal pasti dan diubah suai untuk simulasi aliran udara dengan tepat dalam busa logam kerana strukturnya yang rumit.Objektif projek ini adalah untuk membuat model saluran yang diisi sebahagiannya dengan medium berliang serta menganalisis tingkah laku aliran bendalir dan penurunan tekanan pada saluran yang telah diisi sebahagian dengan blok berliang aluminium sel terbuka. Busa aluminium sel terbuka dengan ketumpatan berlainan, 5, 10 dan 30 liang per inci PPI telah dipertimbangkan, termasuk ketebalan busa dan halaju masuk. Perkomputeran Dinamik Bendalir (CFD) dijalankan berdasarkan eksperimen yang dibuat oleh kajian sebelumnya untuk mendapatkan data yang lebih tepat. Formula Ergun-Forcheimmer telah digunakan untuk menentukan kelikatan dan inersia dalam domain medium berliang manakala persamaan Navier-Stokes telah digunakan untuk kawasan yang jelas.Konfigurasi saluran dua dimensi (2D) dibentuk kerana ukurannya yang simetri. Pengesahan dengan busa logam 20 PPI daripada literatur lain telah dibuat.Keputusan yang diperoleh dari simulasi CFD boleh diterima. Melalui simulasi yang dilakukan, pengedaran halaju dalam saluran diperiksa terutamanya pada tingkah laku aliran bendalir di bahagian hulu, tengah, dan hilir saluran.Penurunan tekanan juga diperiksa dengan memerhatikan konturnya. Selain itu, perbandingan kelajuan dan tekanan antara data eksperimen dan simulasi juga ditunjukkan dalam bentuk carta termasuk kajian sebelumnya. Oleh itu, tingkah laku aliran di kawasan hulu dan hilir yang berkaitan dengan projek ini juga telah dijelaskan.

`

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude and the deepest appreciation to my supervisor Dr. Fadhilah binti Shikh Anuar for the guidance and endless support towards the completion of this final year project with smoothness.

I would also like to show gratitude to Dr. Nazri bin Md Daud and Dr. Mohamad Firdaus bin Sukri as my examiners for giving me useful advices and suggestions upon the completion of this project. Their co-operation is highly appreciated. Million thanks to Universiti Teknikal Malaysia Melaka (UTeM) for giving me a chance to participate and to gain experience in handling a final year project. Furthermore, I would like to thank all my friends for helping and giving me pieces of advices throughout the completion of this final year project.

Last but not least, not to forget to express my deepest sense of gratitude to my beloved parents and siblings for their never endless encouragement. They gave me a lot of persistence in not giving up to do my best in the project.

TABLE OF CONTENTS

`

`

LIST OF FIGURES

`

`

`

LIST OF TABLES

`

LIST OF ABBREVIATIONS

PIV	Particle Image Velocimetry

LIST OF SYMBOLS

d_p = pore diameter (m)

h = foam height (m)

H = channel height (m)

H_f = free stream region height (m)

h/H = blockage ratio

K = permeability (m^2)

L_c = length of channel (m)

PPI = pore per linear inch

U_o = inlet velocity (m/s)

U_s = upstream velocity (m/s)

U_p = average pore velocity (m/s)

∇p^* = pressure gradient of flow direction ($\Delta p/\Delta x$)

u^* = flux per unit area of the porous medium (Φ/m^2)

ε = porosity (-)

μ = dynamic viscosity (kg/(m.s))

v = kinematic viscosity (kg/(m.s))

ρ = density (kg/m^3)

β = inertial resistance coefficient (-)

`

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Generally, configurations of having a part of the passageway filled with the metal foam or any type of material are called a partially filled channel. The partially filled channel can be divided into three sections which are upstream, free stream, and downstream region. The upstream is a region where the input of fluid and downstream is a region where low-velocity air merges with high-velocity air. The free stream region is a non-porous region on the metal foam [1]. The partially filled channel is used to minimise the pressure drop in the fluid flow compared to fully-filled channel [2]. The high-pressure drop of a fully-filled channel reduces the performance of the system and consumes a large amount of energy. Other than that, fully filled channel reduces the velocity of fluid flow compared to the partially filled channel [3].

One of the main properties of metal foam is permeability. Permeability (K) measures the capability to transmit fluids through a porous medium. The permeability can be divided into three categories; absolute permeability relative permeability and affective permeability [9]. It shows the ability to transmit fluids across the porous medium. The critical pore size gives an impact on the permeability of porous media [10]. The examples of permeable media in nature are the sand beds and limestone [11]. Other important properties of the metal foam are porosity (ε), which is defined as the ratio of the volume of pore space divided by the total volume [5].

`

There are many types of metal foams in the market. Some of the examples are copper foam, aluminium foam, silicon carbide foam and zirconium oxide foam. It can be either closed-cell foam or open-cell foam. The open-cell metal foam is a cellular structure made up of solid metal with a large volume fraction of gas-filled pores. Each of the metal foam has its properties and applications. For example, the open-cell metal foams used as the replacement of conventional fins used in aerospace as this metal foam could provide higher surface area to volume ratio with marginally increased in pressure drops values [4]. The expensive honeycomb structure can be replaced by metal foam sheets or sandwich panels in the aerospace industry. It can reduce cost and retain the integrity of the structure from any case of fire. Other than that, metal foam preferred for their lightweight properties.

In the automotive industry, metal foams reduce the number of parts in the car frame thus reduces the cost and increases the performance [5]. The good relation between stiffness and weight support of metal foam makes it suitable for large-area light parts with increased requirements on stability. Examples are engine hoods and trunk lids. The metal foam is used to strengthen the protection inside of the trucks. In rear and front car bumpers, it is used as energy-absorbing structures. While in furniture and household industry, metal foams can be used in lamps and tables. Its combination with the wood surface can give new effects in the room. Lightweight furniture can be a great advantage in fairs or exhibitions to be moved from one place to another. For the construction and building industry, the metal foam has excellent fire penetration resistance and thermal insulation properties. Due to their thermal insulation properties, it can be used as energy-saving elements. They are being used beneath highway bridges, building interior and railway tunnel for their sound-absorbing properties. It is also perfect for ceilings and roofs due to their lightweight and easy to be installed without any mechanical lifting equipment. The other application of open-cell metal foams is for filtration [6], sound absorption [7] and medical devices [8].

`

Commonly, the metal foams properties are classified based on their pores densities (PPI) e.g. 5, 10 and 30 PPI. A proper selection of pore density is important to ensure a suitable amount of fluid or air flows into porous region instead of the non-porous region. This is because the pore density affects metal foam performance and functionality such as heat exchangers. Many studies [11] agreed that metal foam efficiency also depends on the porosity in addition to the PPIs. Metal foam is defined as porous media in numerical studies. The interface of the porous medium has to be assumed and remodelled to improve the airflow in metal foam because the metal foam multi-struts interconnected to each other. However, the interface condition of the metal foam remains debated due to complex interface condition and flow behaviour at those regions [12].

To describe the flow of fluid through a porous medium, the Darcy equation can be used. However, there are four conditions for Darcy Equation to be applicable; (1) laminar flow in the porous medium, (2) porous media should not interact with fluid, (3) no accumulation and (4) creeping flow [4]. Darcy law has a low Reynolds number. However, with higher porosity configurations, range from 0.90 - 0.97 and also high permeability, Darcy model cannot give precise answers [13].

This Brinkman term in momentum gives a more precise mathematical model when the inertial term is significant. The Brinkman equation used to justify the flow by considering different parameters such as fluid velocity, pressure and gravitational potential. Meanwhile, the Navier-Stokes equation is used to explain fluid flows in clear domains. This equation is used when the viscosity is crucial. While the Forchheimer equation can be used for flow with higher Reynold number specifically for this condition; (1) turbulent flow in a porous medium and (2) viscous and inertial effect are more crucial [14]. The Reynolds number for fluid flow in porous medium are $Re < 1$ (Creeping flow), $1 < Re < 10$ (Inertial flow regime), $150 < Re < 300$ (Laminar flow) and $Re > 300$ (Turbulent flow) [15].

`

1.2 PROBLEM STATEMENT

Metal foam is designed as a porous medium in numerical studies using ANSYS Fluent. The common pore density of open-cell metal foam used in experiments is 5, 10, 20, and 30 PPI. Pore density stands for the number of pores per one inch in a metal foam. Note that, low PPI foam has larger size pores compared to high PPI foam. It was concluded in [1] that for the low PPI foams with higher blockage ratio, the momentum of airflow maintains its consistency until the end of the foam.

On the other hand, for high PPI foam, the airflow tends to search a way out by entering the nearer pores which causes the momentum of the airflow to drop and the air flows towards the interface [12]. There are three main reasons for variation of pressure drop due to high blockage ratio; (1) different metal foams pore density and sizes used, (2) flow separation in the channel due to the existence of porous medium block and (3) formation of wakes at the downstream of the foam block.

For the 5 and 10 PPI metal foam which blocks that partially filled channel, the airflow passes through the open-cell aluminium foam from the entrance toward the foam end without entering non-porous region but with 30 PPI the air flows into the non-porous region on the top of the foam block before reaching the foam end. The formation of the recirculating zone at downstream region was caused by the increase of free stream velocity with the blockage ratio. Interestingly, this situation occurs with the high PPI foam and solid block but not with the low PPI foam [1]. Unfortunately, past numerical studies [16] could not capture such flow behaviours. This is because the fluid flow in porous media does not have a constant movement that can be measured.

`

Suitable parameters have to be identified for the partially filled channel; eg: pore density, foam length and blockage ratio to make sure the unique structure of the porous foam can be fully utilized. The interface of the porous medium has to be identified and remodelled to simulate the exact airflow in metal foam because the metal foam multi-struts interconnected to each other and the interface condition of the porous media remains a debated issue.

1.3 OBJECTIVE

The objectives of this project are as follows:

1. To model a partially filled channel with a porous medium.
2. To investigate the fluid flow behaviour and pressure drop in a partially filled channel with different properties of the porous medium.

1.4 SCOPE OF PROJECT

This project studied inertial resistance and other properties by modelling a porous medium in a partially filled channel. Only results of the simulation are presented in this report using the dimensions of the wind tunnel and aluminium foam with the pore densities are obtained from other literature [1]. The Finite Volume-based Software ANSYS Fluent is used to simulate the porous media in the partially filled channel. Limited parameters are introduced in the simulation such as the pore densities (5, 10, and 30 PPI), blockage ratio (the difference between channel and porous block height) and inlet velocity (3.9, 5.5, 6.2, 6.5, 9.5 and 12.5 m/s).

`

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter has four main sections which explain the fluid flow and pressure drop of air in a partially filled channel with porous medium. The metal foam physical properties are shown in section 2.2. The equations for flow in porous media are discussed in section 2.3. Additionally, previous studies on the metal foam will be discussed in section 2.4 and 2.5, including both experimental and numerical studies which are related to this project.

2.2 METAL FOAM AND PHYSICAL PROPERTIES

Metal foam can be either closed-cell foam or open-cell foam. Each of the metal foam has its properties and applications. There are different types of materials manufactured for metal foam such as aluminium, copper and titanium. The open-cell metal foam is a cellular structure made up of solid metal with a large volume fraction of gas-filled pores. Open-cell metal foam has good permeability, high strength and high specific surface. Moreover, the foam can be used for medical purposes such as bone replacement [17].

`

On the other hand, closed-cell metal foam is stiff at low weight and effective in structural damping with electromagnetic shielding. These metal foams also are being used for engineering applications such as filtration [6] and sound absorption [7]. There are few ways for metal foam manufacturing including casting, metallic deposition and powder metallurgy. No matter which method is used to form the metal foam, they are still differentiated by labelling either poor quality or high cost [18].

Table 2.1: Open-cell aluminium metal foam properties [19]

Parameters	**Values**
Foam topology	Open, interconnected
Standard cell size, d_p (cm)	2 to 16 pores
Relative density (%)	4 to 10
Melting point (^oC)	660
Compression/tensile/shear strength (MPa)	2.53 /1.24 / 1.31
Specific heat, C_p (J/g-C)	0.895

The physical properties of open-cell aluminium foam other than **Table 2.1** are such as permeability (K) porosity (ε), and pore diameter (d_p) depends on pore density (PPI) of the foam. When the pore size increases, the permeability also increases together with the porosity (ε) [20].

2.3 EQUATIONS FOR FLOW IN POROUS MEDIA

2.3.1 Pressure drop

Pressure drop, ΔP is one of the parameters used to understand the fluid flow through a porous medium of different pore densities (PPI). For laminar flow, the pressure drop is calculated as [21]: