CFD STUDY OF OSCILLATORY FLOW ACROSS POROUS STRUCTURE

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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A report submitted
in fulfilment of the requirements for the degree of
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DECLARATION

I declare that this project report entitled "CFD Study of Oscillatory Flow across Porous Structure" is the result of my own work except as cited in the references.

Signature : ____________________

Name : PETER TAN LUI MING

Date : 16/7/2021

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.

Signature : ____________________

Name of Supervisor : DR. FATIMAH AL-ZAHRAH BINTI MOHD SA'AT

Date : 16/7/2021

ABSTRACT

The oscillatory flow across porous structure is a typical feature in thermoacoustic system, by using the CFD software to study the thermoacoustic system, the flow can be visualised and analysed easily. The two objectives of the project are to model the oscillatory flow in thermoacoustic refrigeration system and also to study the effect to the flow and thermoacoustic performance by changing the working fluid in the thermoacoustic refrigeration system. In this study, the 2D oscillatory flow in thermoacoustic refrigeration system is successfully modelled by using dynamic mesh method to prevent the backflow of the inlet. There are four working gases that are compared in this study, air and three different noble gases, helium, neon and argon. The operating parameters is designed based on each working gases. The results show the noble gases provide a better thermoacoustic effect after the approximately same time period (0.1s). Helium as working fluid shows the best performance in terms of temperature differences at the stack of 0.528°C. The recommendations for further study of CFD of oscillatory flow across porous media in thermoacoustic refrigeration system are also suggested.

ABSTRAK

Aliran berayun melintasi struktur berpori merupakan sesuatu ciri khas dalam sistem termoakustik, dengan menggunakan perisian CFD untuk mempelajari sistem termoakustik, alirannya dapat digambarkan dan dianalisis dengan mudah. Dua objektif dalam projek ini adalah untuk memodelkan aliran berayun dalam sistem penyejukan termoakustik dan juga untuk mengkaji kesan terhadap prestasi aliran dan termoakustik dengan mengubah cecair kerja dalam sistem penyejukan termoakustik. Dalam kajian ini, aliran berayun 2D dalam sistem penyejukan termoakustik berjaya dimodelkan dengan menggunakan kaedah jejaring dinamik untuk mengelakkan aliran balik di saluran masuk. Terdapat empat gas kerja yang dibandingkan dalam kajian ini, udara dan tiga gas adi yang berbeza, iaitu helium, neon dan argon. Parameter untuk operasi sistem dirancang berdasarkan setiap gas kerja yang digunakan. Hasilnya menunjukkan gas adi dapat memberikan kesan termoakustik yang lebih baik berbanding dalam jangka masa yang hampir sama (0.1s). Cecair berfingsi helium menunjukkan prestasi terbaik dari segi perbezaan suhu 0.528°C pada timbunan. Cadangan untuk kajian lebih lanjut mengenai CFD untuk aliran berayun melintasi media berpori dalam sistem penyejukan termoakustik juga telah dicadangkan.

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LIST OF ABBREVIATIONS

2D	-	Two Dimensional
3D	-	Three Dimensional
ANSYS	-	Analysis System
CFD	-	Computational Fluid Dynamic
CHX	-	Cold Heat Exchanger
COP	-	Coefficient of Performance
DeltaEC	-	Design environment for low amplitude thermoacoustic Energy Conversion
HFCs	-	Hydrofluorocarbons
HHX	-	Hot Heat Exchanger
PISO	-	Pressure-Implicit with Splitting of Operators
PRESTO!	-	PREssure STaggering Option
SWTAR	-	Standing Wave Thermoacoustic Refrigerator
TAR	-	Thermoacoustic Refrigerator
TPV	-	Thermophotovoltaic

TWTAPM	-	Traveling Wave Thermoacoustic Prime Mover
UDF	-	User Defined Function
RVC	-	Reticulated Vitreous Carbon

LIST OF SYMBOLS

g	-	Gravitational acceleration
v	-	Moving wall velocity
ω	-	Angular velocity
t	-	Time taken
k	-	Thermal Conductivity
C_p	-	Specific Heat Capacity
λ	-	Wavelength of sound
c	-	Speed of sound
f	-	Oscillation frequency

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, most people use conventional refrigerator that function using the refrigeration cycle. The refrigeration cycle as shown in Figure 1.1, consists of four major components, compressor, condenser, expansion valve and evaporator. Inside the cycle system, will be flowing with the refrigerant for heat transfer, and one of the commonly used refrigerant is Hydrofluorocarbons (HFCs).

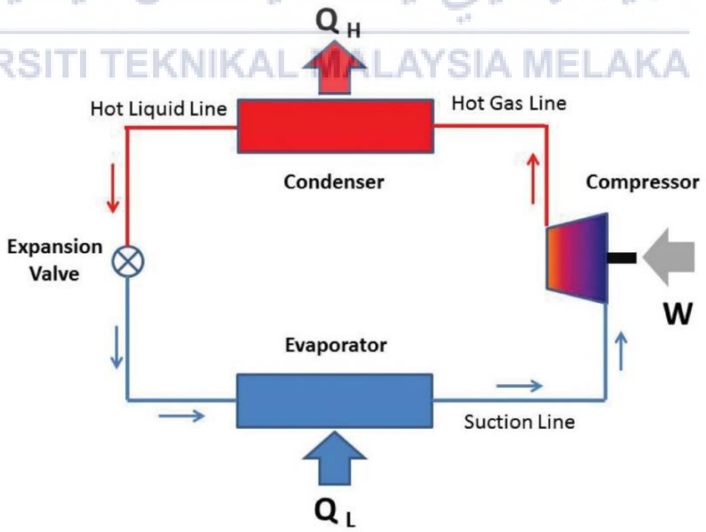

Figure 1.1: Basic Refrigeration Cycle

(Retrieved from: https: //insulation.org/io/articles/understanding-thermal-systems-industrial-refrigeration-systems/)

Even though conventional refrigerator is commonly used, there are few problems on using it. Firstly, the compressor in the refrigeration cycle contains many mechanical moving parts. This causes the increase of cost that need to repair the system in time. Secondly, most of the commonly use refrigerant causes harmful effect on the environment. For example, HFCs even though a non-ozone depleting refrigerant, could cause global warming as it is a type of potent greenhouse gases. To avoid the problems of conventional refrigerator, one of the alternative is the Thermoacoustic Refrigerator (TAR).

Thermoacoustic, basically relates to heat and sound waves. Thermoacoustic energy system has the ability to either convert the heat energy into work or convert from work into heat energy in the form of acoustic energy. The thermoacoustic engine and refrigerator is shown in Figure 1.2.

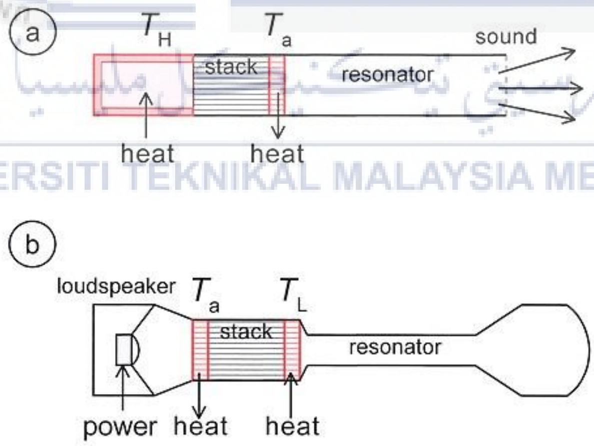

Figure 1.2: Schematic diagram of thermoacoustic a) Prime mover and b) Refrigerator (Retrieved from https://en.Wikipedia.org/wiki/Thermoacoustics)

The theory behind the thermoacoustic energy system, taking thermoacoustic refrigerator as an example, is that the power from the acoustic driver produces sound energy that drives the vibration to the gas particle inside. The stack inside the resonator tube act as an insulator of heat. When the vibration in the tube occurs, the heat from one side will not transfer to the other side too quickly, creating a temperature gradient in the stack, and the heat will instead transfer to or from the wall of the tube.

The stack can be said as the heart of the thermoacoustic device. It is made from large number of closely spaced surfaces aligned parallel to the resonator tube. The stack insulates the heat while allowing the oscillation of the gas inside the tube. Since the stack consist of many fine layer of closely spaced surface, it can be seen as a type of structured porous media.

Oscillatory flow is a type of repetitive variation flow of fluid which can be commonly found in sound waves, a type of mechanical waves. When the oscillatory flow passes through a porous media, the porous media will affect the flow in the system. This type of oscillatory flow can be found in thermoacoustic energy system, in which the source of energy of the system, is provided by the oscillating sound waves from the acoustic driver.

1.2 Problem Statement

In conventional refrigerator system, the flow of refrigerant can be easily described as one directional flow in the cycle when heat exchanging. However, for thermoacoustic refrigerator, the flow is an oscillatory flow, which vibrates back and forth in the tube. The oscillating flow across the stack which is a type of structured porous media is very hard to predict and visualise. If experiment is done to find out characteristic of this flow, it will cost a lot of money and time. Therefore, doing a well design computational fluid dynamic (CFD) simulation study, it is able to provide a clear picture and the parametric investigation can be done easily.

1.3 Objectives

The objectives of this study are:

i. To model an oscillatory flow across porous structure of a thermoacoustic refrigerator.

ii. To investigate the effect of type of working fluid to the flow and performance of thermoacoustic refrigerator.

1.4 Scope of study

This project will be carried out only numerically with the CFD software. The study will cover equations of moving boundary to simulate the acoustic driver source for CFD. Also, the simulation of fluid dynamic and heat transfer across the porous media will be studied. Moreover, the effect of using dynamic mesh in thermoacoustic refrigeration simulation will be investigated. Additionally, the effect of different working fluid to the flow and heat transfer in the thermoacoustic refrigerator will be studied.

CHAPTER 2

LITERATURE REVIEW

2.1 Porous Media

According to Badruddin, et al. (2020), porous media can be said as a solid medium matrix with interconnected void. The fluid is able to flow across the empty spaces between the matrix arrangement of solid, allowing the convective heat transfer of the fluid and the solid (Badruddin, et al., 2020). Badruddin, et al. (2020) also mentioned porous media can be natural or artificial, where examples of natural porous media include limestone, sand, soil, natural organs, while examples of artificial porous media include cigarettes, cloths and so on. In the mini review of Badruddin, et al. (2020) shows that many other researcher study on the heat transfer involving porous media, the studies do not only limit to convection and conductive but also radiative heat transfer. Figure 2.1 shows the 3D geometric model of the flow and heat transfer study of porous media by Li, et al. (2020).

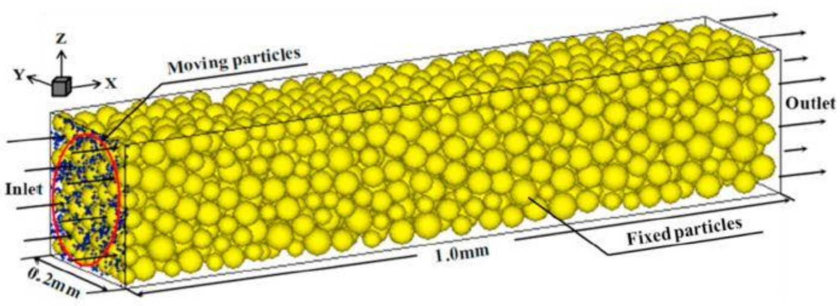

Figure 2.1: 3D geometric model of porous media (Li, et al., 2020)

2.1.1 Studies of Porous Media

There are many uses of porous media. In a study by Quaye, et al. (2020), porous media are used with the micro combustor to improve the performance of the Thermophotovoltaic (TPV) power generation. Ferrari, et al. (2014) describe the TPV system is able to do conversion from the radiant energy from the combustor into electrical energy at the photovoltaic cells, the porous media used is function as an emitter in the TPV system. Porous media combustor has few advantages compared to non-porous media combustor, such as high burning rates, power dynamic range, low emissions of carbon monoxide, nitrogen gases and soot which are hazardous to environment (Quaye, et al., 2020). Figure 2.2 shows the schematic of combustion chamber using methane-oxygen as fuel for combustion, where porous media is placed at the around the side of the cylindrical combustion chamber.

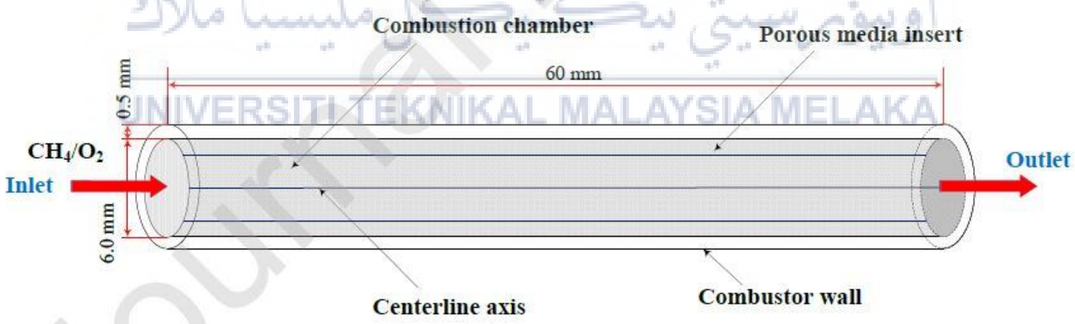

Figure 2.2: Schematic of combustor used in experiment (Quaye, et al., 2020)

Another study of fluid flow on porous media by Siddiqui and Azim (2020), it is about the reabsorption of substances through the renal tubule cell walls which act as a porous media when the renal tubule gets diseased. When the renal tubules get certain disease, the porosity of the tubules could be affected and there could be protein like albumin lost to the urine through renal tubules (Siddiqui and Azim, 2020). Figure 2.3 shows the schematic diagram of flow through porous slit of the renal tubule.

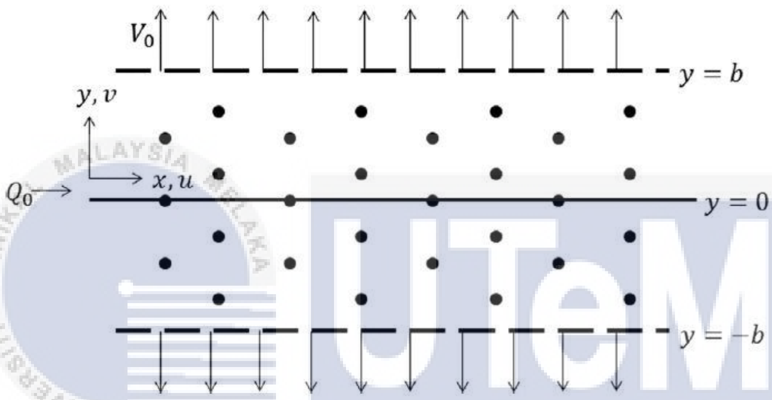

Figure 2.3: Schematic diagram of flow through porous slit (Siddique and Azim, 2020)

Baragh, et al. (2019) did an experimental study on mist flow and heat transfer in tube fitted with porous media. Baragh, et al. (2019) study is done on 6 different model of porous media, where the flow is through a heated cylindrical test section by constant heat flux, and 24 thermal sensors across the test section to show the channel temperature. In Figure 2.4 shows the experimental setup, and Figure 2.5 show the schematic of porous media models used in the test. The porous medium inserted is able to significantly increase the heat transfer rate occurring between surface of a channel and the mist air flowing inside the heat exchanger (Baragh, et al., 2019).

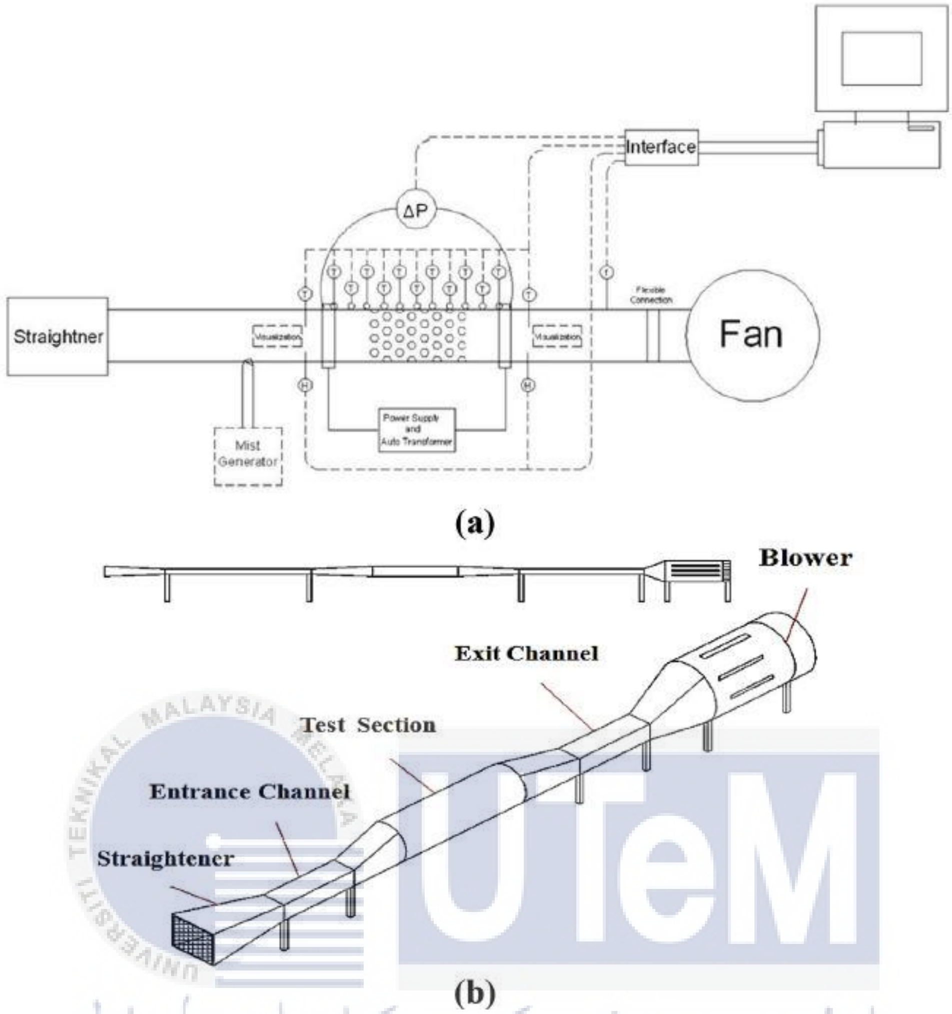

Figure 2.4: Experimental Setup for testing heat transfer with mist flow and porous media (Baragh. et al., 2019)

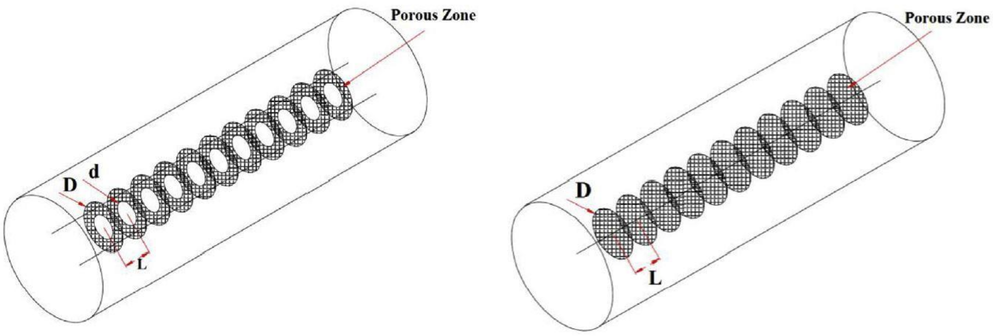

Figure 2.5: Schematic diagram of porous media model used in test (Baragh, et al., 2019)

2.2 Oscillatory Flow

The oscillating flow fluid moves backwards periodically, causing the vortex wake formed at the first half-cycle of oscillation to sweep back during the subsequent half-cycle (Okajima, et al., 1997).

In an experimental study by Munoz-Camara, et al. (2020) on oscillatory flow in circular tubes with orifice baffles, the oscillatory flow is created by using a hydraulic cylinder (10) driven by a crank and connecting rod (12) arrangement as shown in Figure 2.6.

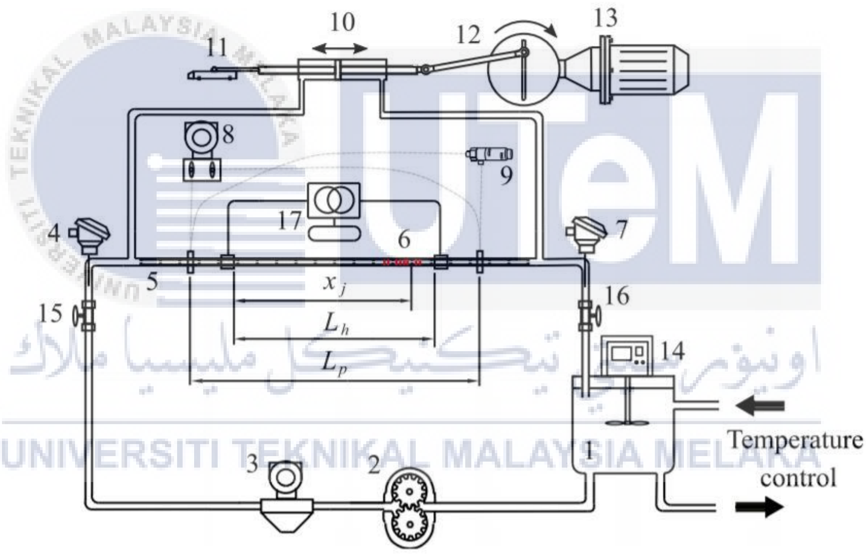

Figure 2.6: Experimental set-up (Munoz-Camara, et al., 2020)

Another research from Chen, et al. (2018), shows the oscillatory flow can be induced by flame pulsation in a confined compartment through a horizontal opening, the vent flow oscillatory behaviour is characterised by the oscillatory frequency of the smoke gas area.

A numerical study by Jiang, et al. (2016) investigates the oscillating flow that is driven acoustically around the coal particles in power plant boiler, the purpose of the acoustic