THE EFFECT OF FREQUENCY ON FLOW AND HEAT TRANSFER OF A HEAT EXCHANGER IN AN OSCILLATORY FLOW CONDITION

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SUPERVISOR DECLARATION

"I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for award of the degree of Bachelor of Mechanical Engineering (Material & Structure)"

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Date: 27 MAY 2015

DECLARATION

"I hereby declare that the work in this report is my own except for summaries and quatations which have been duly acknowledged."

Signature: ……………………………
Author: ……………………………
Date: ……………………………

Special for my beloved mum SHAMSIAH BTE MOHD and my fabulous dad MOKHTARUDDIN BIN ABD MANAF

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ABSTRAK

Projek ini bertujuan untuk menyediakan dan membangunkan model *Computational Fluid Dynamic* (CFD) yang membolehkan asas pemindahan haba dan kajian menganai aliran ayunan dalam sistem termoakustik. Pemahaman kepada keadaan aliran ayunan adalah penting untuk memperbaiki dan meningkatkan keberkesanan sesuatu sistem. Di sini, fokus khusus kajian adalah tentang mencari kesan frekuensi pada aliran haba dan pemindahan penukar haba dalam keadaan ayunan. Pada asasnya, kelajuan aliran dalam sistem sangat bergantung kepada aliran frekuensi. Aliran ini akan bergerak lebih cepat dengan frekuensi yang lebih tinggi. Dari sudut yang lain, kedalaman interaksi haba antara permukaan pepejal dan gas yang digunakan juga bergantung kepada frekuensi. Oleh itu, lapisan haba menjadi lebih nipis. Dengan pembangunan model CFD ini, frekuensi yang berbeza akan digunakan untuk menganalisis dan membincangkan bagaimana ia akan memberi kesan kepada sistem. Hasilnya kemudian akan disahkan dengan teori atau keputusan eksperimen yang telah ada.

ABSTRACT

This work aims to setup and develop a Computational Fluid Dynamic model (CFD) that enables fundamental heat transfer and oscillatory flow studies in thermoacoustic system. The understanding of the oscillatory flows conditions is important to improve and increase the effectiveness of the system. Here, the particular focus is on the effect of frequency on flow and heat transfer of a heat exchanger in a oscillatory condition. Basically, the rapidness of the flow in a system really depends on the flow frequency. The flow will moves faster with higher frequency. In the other hand, the depth of thermal interaction between the solid surface and the following gas also depends on the frequency. Therefore, the thermal layer will becomes thinner. With development of the CFD model, the different frequencies will be used to analyse and discuss how it will affect the system. The result then will be validated with available theory or experimental findings.

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ω	=	Angular frequency, rad/s
^{o}	=	Degrees angle
ρ	=	Density, kg/m^3
D	=	Diameter, m
d	=	Distance, m
D_r	=	Drive ratio, %
f	=	Frequency, Hz
Q_c	=	Quantity of heat, J
Q_h	=	Excess heat, J
C_p	=	Isobaric specific heat, J/g$\cdot$K
ν	=	Kinematic viscosity, m^2/s
$\dot{m}$	=	mass flow rate, kg/s
m_2'	=	mass flux, kgs^{-1}m^{-}
m	=	metre
mm	=	milimeter
π	=	Pi
W_{ac}	=	Acoustical power, kW
P	=	Pressure, kPa
P_a	=	Oscillating pressure, kPa
k	=	Thermal conductivity, W/m$\cdot$K
θ	=	Theta
T	=	Temperature, K
δ_k	=	Thermal penetration depth
Re	=	Reynold's number
c	=	Speed of sound, m/s

V_{avg}	=	Average velocity, m/s
v	=	Velocity, m/s
μ	=	Dynamic viscosity, kg/m·s
λ	=	Wavelength, m
k_a	=	Wave number
V_e	=	Variation of the voltage amplitude, V
V	=	Voltage

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Heat transfer processes in the presence of oscillatory flow has received a lots of research interest in the past few decades. The heat transfer enhancement due to the oscillatory flow may lead to a large variety of possible application. Thus, a large number of experimental and numerical works have been carried out and analysed. A variety of the devices may be related to this process such as Stirling engines or coolers, thermoacoustic devices and pulse tube coolers. These devices employ the oscillatory gas flow as the working fluid as a means of energy transfer. Therefore, the design of heat exchangers, stack or regenerators and thermal buffer tube in such devices requires the understanding of the heat transfer process between the solid boundary and oscillatory gas flow.

Understanding of heat transfer process between a solid boundary and a flowing fluid is important for the design of internal components such as heat exchangers, regenerators and thermal buffer tubes in thermoacoustic and Stirling thermodynamics machines where the flow oscillations are parts of the power production or transfer process.

Oscillatory flow is also a method of mixing materials using the combination of sharp edge and a periodically reversing flow in a tube or a channel, which has potential applications in several fields. It is the oscillatory flow which controls the mixing and this is controlled by varying the frequency and amplitude of the oscillation.

A sound wave commonly consist of coupled pressure and motion oscillations. However, for devices that produce energy, temperature oscillations are constantly present. When the sound travels in small channels, oscillating heat also flows to and from the channel walls. The combination of all such oscillations produces a rich variety of "thermoacoustic" effects. Thermoacoustics research began with curiosity about the oscillating heat transfer between gas sound waves and solid boundaries. These interactions are too small to be obvious in the sound in air with which we communicate every day. Nevertheless, in intense sound waves and pressurized gases, thermoacoustics can be harnessed to produce powerful engines, refrigerators, pulsating combustion, heat pumps, and mixture separators. Therefore, a lot thermoacoustics research in the immediate past is motivated by the desire to create new technology for the energy industry that is as simple and reliable as sound waves themselves.

In this paper the study and analysis about the effect of frequency on heat transfer of an oscillatory flow. What will happen with the oscillatory flow and the heat transfer if the frequency changes? Theoretically, the frequency can affect many element in the system of heat transfer. Thus, the relationship between those need to be find out.

1.2 PROBLEM STATEMENT

The rapidness of oscillatory flow depends on the flow frequency. Flow with high frequency moves very fast. The fast movement may leads to a change in flow behaviour in an unexpected ways. In addition, the depth of thermal interaction between solid surface and the flowing gas also depends on the frequency. The depth decreases as the frequency increases. Consequently, the thermal layer becomes thinner. This theoretically, will affect the heat transfer between the solid surface and the gas or medium. For a flow across a heat exchanger, the changes of frequency will affect the flow and heat transfer within the area. There are many studies related to flow and heat transfer within a heat exchanger. However, most studies are related to a steady flow. Studies related to oscillatory flow conditions are therefore necessary.

1.3 MOTIVATION OF STUDY

The oscillatory flows mechanisms and impact on heat transfer performance of devices are not well understood. This effect may bring negative or positive impact to the system. For a thermoacoustic devices, the detail understanding of the behaviour of oscillatory flow within the device is vital as it may assist in improving the efficiency and performance of the system. Devices utilising thermoacoustic principles are attractive because they involve simple mechanisms and use environmentally friendly gas as the working medium. These qualities encourage lots of research works within the field with hopes that this attractive technology will soon enough have its own place in the industry.

1.4 OBJECTIVE

1. To study the theory of heat transfer and of an oscillatory flow condition.
2. To setup and develop suitable Computational Fluid Dynamics (CFD) model.
3. To validate the result obtained with the existing theoretical calculation result.
4. To study and understand the heat transfer process between a solid boundary and oscillatory fluid flow due to the change of frequency.

1.5 SCOPE

The oscillatory condition investigated is limited to thermoacoustic flow condition. The heat exchanger will be placed in a specific condition of thermoacoustic environment. The scope of this study is to set up a CFD model that is able to investigate the effect of frequency in two dimensions (2D). The model will be validate with theoretical prediction and available experimental findings. In this paper, the study will be concentrate on the effects of the change of the frequency on flow and heat transfer across a parallel-plate heat exchanger.

CHAPTER II

LITERATURE REVIEW

2.1 FUNDAMENTAL OF FLOW AND HEAT

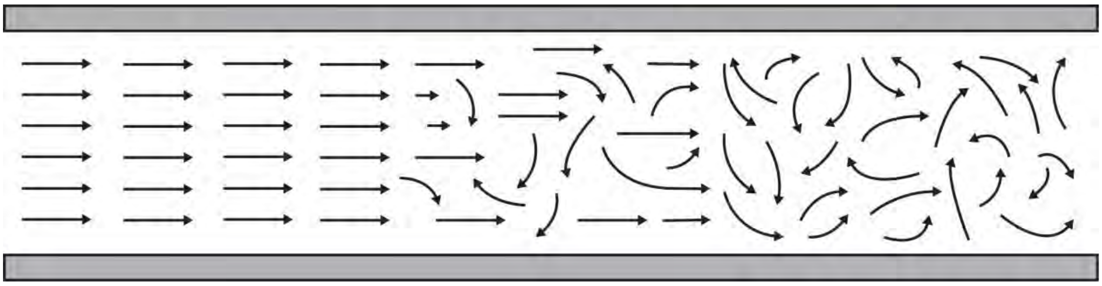
Subramaniam (2003) explain about the introduction of heat transfer with the principal differences between heat transfer in laminar flow and in turbulent flow. The value of Reynolds number, Re, defined in equation (2.1) permits us to determine wether the flow is laminar or turbulent.

$$\mathrm{Re} = \frac{V_{avg} D}{v} = \frac{\rho V_{avg} D}{\mu} = \frac{\rho D}{\mu}\left(\frac{\dot{m}}{\rho \pi D^2 / 4}\right) \qquad (2.1)$$

In equation (2.1), the term D is the inside diameter of the tube (or pipe), V is the average velocity of the fluid, ρ is the density of the fluid and μ is its dynamic viscosity. It is sometimes useful to use kinematic viscosity $v = \mu / \rho$ in defining the Reynolds number. Another common form involves using the mass flow rate, $\dot{m}$, instead of the average velocity. The mass flow rate is related to the volumetric flow rate via $\dot{m} = \rho \dot{Q}$, and can be written as $\dot{Q} = \pi D^2 V / 4$. Therefore, the Reynolds number can also be defined as :

$$\mathrm{Re} = \frac{4\dot{m}}{\pi \mu D} \qquad (2.2)$$

The flow in a commercial circular tube or pipe is usually laminar when the Reynolds number is less than 2300 (Re < 2300). In the range of (2300 < Re < 4000) the status of the flow is in transition and for (Re > 4000) , flow can be regarded as turbulent. Under most practical condition, the flow in a tube is laminar for Re < 2300, fully turbulent for Re > 10000, and transitional in between. But it should keep in mind that in many cases the flow becomes fully turbulent for Re > 4000. (Cengel, 2011)



Laminar $Re < 2\,300$ | Transition $2\,300 < Re < 4\,000$ | Turbulent $Re > 4\,000$

Figure 2.1: Illustration of laminar, transition and turbulent flow.
(Source: Flowcontrolnetwork.com, (2010))

Xia et al. (2014) studied about the effects of different geometric structure on fluid flow and heat transfer performance in microchannel heat sinks. The numerical investigation has been performed to study the effects of the inlet and outlet locations, header shapes and microchannel shapes on fluid flow and heat transfer, and the optimal geometric parameters were obtained.

Yin et al. (2012) made numerical analysis of transitional characteristics of flow and heat transfer in wavy channels. The effects of sinusoidal wavy channel plate spacing, phase shift and Reynolds number, Re, on heat transfer and flow characteristic have been numerically investigated. The calculations are carried out on periodic unit channels with uniform wall temperature. The phase difference between the main stream at core and wall determines flow and heat transfer feature. The minimum frequency value was obtained in 180 degree phase channel with minimum plate spacing, and the maximum frequency value was gained in the same phase channel with the minimum plate spacing.

2.2 HEAT EXCHANGER

Heat exchangers are devices that are used to transfer heat between two or more fluid at different temperatures. They are used in a wide variety of applications such as refrigeration and air-conditioning system, power engineering and other thermal processing plants. In general, the enhancement of heat transfer techniques can be divided into two types, active and passive. The active techniques required external forces such as electric field, acoustic, and surface vibration. Meanwhile the passive techniques required special surface geometries or fluid additives. Naphon and Wongwises (2006). The simplest heat exchanger is one for which the hot and cold fluids move in the same or opposite directions in a concentric tube (or double-pipe) construction. In the parallel-flow arrangement of **Figure 2.2** (a) the hot and cold fluids enter at the same exit, flow in the same direction, and leave at the same end. In the counterflow arrangement, the fluids enter at opposite entrance points, flow in opposite directions, and leave at opposite exit point.

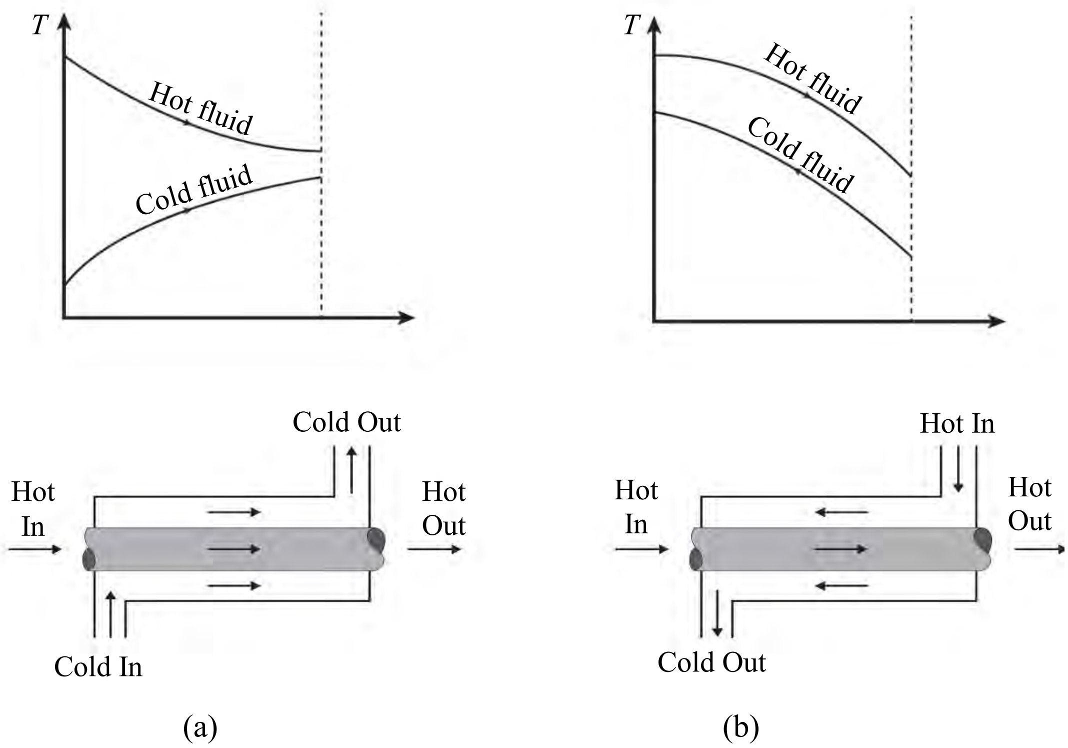


Figure 2.2: Different flow regimes and assiociated temperature profile in double pipe exchangers with (a) parallel-flow and (b) counter-flow. (Cengel and Ghajar, 2011)

Fakheri, A. (2014) studied about the efficiency analysis of heat exchanger and heat exchanger networks. He found that the heat exchanger efficiency was a convenient approach for heat exchanger analysis, and can be used to solve ratio and sizing problems, as well as network of heat exchangers without the need for charts, or complicated performance expression. The efficiency of all heat exchangers were determined from a single algebraic expression. A new expression for direct solution of the sizing problem was presented. A closed form expression for determining the required minimum number of heat exchangers was derived. This paper also presents a new methodology for analysing network of heat exchangers connected in series which allows the direct determination of the size of individual heat exchanger, and rate of heat transfer in them, which shows that the heat transfer rate in consecutive heat exchangers connected in series increases geometrically.

Haris et al. (2002) has fabricated and tested two types of micro-cross-flow heat exchangers. Analytical and numerical models were developed and the models were found to accurately predict the performance of the heat exchangers. The models incorporate, to first order, the prediction that heat transfer or gas channel volume is inversely proportional to scale. The scale of heat exchangers that were fabricated was approximately one order smaller than conventional scale heat exchangers and heat transfer or volume was between 3-7 times greater. One of the suspected reasons for heat transfer or volume ratio which does not strictly follow the scaling prediction was that porosity in conventional scale heat exchangers is higher than micro-heat exchangers. In addition, the scaling law is based only on the volume occupied by the through-plane channels. Nevertheless, relative to a conventional scale heat exchangers, the fabricated heat exchangers provide extremely high rates of heat transfer or volume and relatively high ratio heat transfer for given pressure drops.

Wakeland and Keoliana (2004) performed an experiment on the effectiveness of parallel-plate heat exchangers in thermoacoustic devices. Measurement of heat transferred between two identical parallel-plate heat exchangers, made under conditions of oscillating flow over a range of frequencies an amplitudes, have been analysed with the goal of producing an improved model for use in the design of thermoacoustic devices. The result shows that by decreasing the plate spacing, it cannot always increase the heat transfer. it can always make the effectiveness close