# CFD INVESTIGATION OF CROSS FLOW OVER TUBE BANKS

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**in fulfillment of the requirements for the degree of**
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# DECLARATION

I solemnly declare that this project report entitled "CFD Investigation of Cross Flow over Tube Banks" is the outcome of my own work except as cited in references during the course of my study under the supervision of Dr. Fatimah Al-Zahrah Binti Mohd Sa'at.

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Name of author : ……........................................

Date : …...........................................

**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 : ……........................................

Date : …...........................................

## DEDICATION

I humbly dedicate this project report to my beloved families who always have my back and show unceasing support to me. They have made the fruition of my efforts possible. I also dedicate this project report to the field of research. The contents of this project report should be helpful for future researches and studies. Last but not least, I dedicate this work to the Almighty God, the creator and curator of immeasurable wisdom and knowledge who made everything possible.

**ABSTRACT**

Heat exchangers are devices that facilitate the exchange of heat between two fluids that are at different temperatures while keeping them from mixing. Heat transfer in a conventional heat exchanger usually involves convection in each fluid and conduction through the wall separating the two fluids. Tube banks are usually found within a heat exchanger and circular tube bundle is one of the simplest geometries that is widely used. However, in the recent years, thermoacoustic heat engine has been receiving increased attention. Thermoacoustic engines are devices which use high-amplitude sound wave to pump heat from one place to another. The main difference between conventional heat exchanger and thermoacoustic heat engine is that one uses one-directional steady flow and the other one uses unsteady oscillatory flow. The main purpose of this project is to gain insight into the characteristics of heat transfer and fluid flow of cross flows over tube banks for both steady and oscillatory flows. All flows are investigated under similar operating condition. Two-dimensional numerical CFD model is conducted using finite volume discretization to evaluate the performance of these systems. The effect of cross flows on temperature, velocity, enthalpy (heat flux), and pressure drop are all investigated. Effect of cross flows over tube banks on fluid flow characteristic and heat transfer performance has been investigated. Numerical simulation has been conducted on a design model of circular tube banks with staggered arrangement using commercial CFD package, Ansys Fluent 16.0. Constant variable is the material, in which air will be flowing over tube banks while the tube is made of aluminium. The flow velocity of air is standardized which implies that Reynold number is constant. The manipulating variables are steady flow and transient oscillatory flow. Mesh independence study has been conducted by increasing the number of element. Best grid is the one with 19170 elements. Oscillatory flow model is a wave function and is ran for 7 cycles for stabilization of variables. The results are validated with theoretical results and consistency is achieved. It is found that steady flow with higher Re has better heat transfer performance compared to those with low Re. Oscillatory flow with higher drive ratio has better heat transfer performance. Steady flow has better heat transfer performance compared to oscillatory flow at identical Re. However this statement is inconclusive and more works are required to substantiate it. Recommendation for future work is to develop appropriate correlation or equation to compute heat transfer coefficient for oscillatory cross flow over tube banks.

## ABSTRAK

*Penukar haba adalah peranti yang memfasilitasi pertukaran haba antara dua cecair yang berada pada suhu yang berbeza sambil mengekalkannya daripada pencampuran. Pemindahan haba dalam penukar haba konvensional biasanya melibatkan perolakan dalam setiap bendalir dan konduksi melalui dinding yang memisahkan kedua-dua cecair. Bank-bank tiub biasanya dijumpai dalam penukar haba dan berkas tiub adalah salah satu geometri paling mudah yang digunakan secara meluas. Walau bagaimanapun, pada tahun-tahun kebelakangan ini, enjin panas thermoacoustik telah menerima perhatian yang semakin meningkat. Enjin thermoacoustik adalah peranti yang menggunakan gelombang bunyi amplitud tinggi untuk mengepam haba dari satu tempat ke tempat lain. Perbezaan utama antara penukar haba konvensional dan enjin haba thermoacoustik adalah bahawa yang konvensional menggunakan aliran mantap satu arah manakala thermoacoustik menggunakan aliran ayunan yang berubah dengan masa. Tujuan utama projek ini adalah untuk mendapatkan gambaran tentang ciri-ciri pemindahan haba dan aliran bendalir aliran bersilang ke atas bank tiub untuk kedua-dua aliran yang stabil dan berayun. Semua aliran disiasat di bawah keadaan operasi yang sama. Model CFD berangka dua dimensi dijalankan menggunakan kaedah pemecahan isipadu jumlah terhingga untuk menilai prestasi sistem-sistem tersebut. Kesan aliran bersilang pada suhu, halaju, entalpi (fluks haba), dan kejatuhan tekanan semua disiasat. Kesan aliran rentas ke atas bank tiub pada ciri aliran cecair dan prestasi pemindahan haba telah disiasat. Simulasi berangka telah dilakukan pada model reka bentuk bank tiub bulat dengan susunan berperingkat menggunakan pakej CFD komersil, Ansys Fluent 16.0. Pemboleh ubah malar adalah bahan, di mana udara akan mengalir ke bank-bank tiub sementara tiub tersebut terbuat dari aluminium. Halaju aliran udara diseragamkan yang menunjukkan bahawa bilangan Reynold adalah malar. Pemboleh ubah manipulasi adalah aliran mantap dan aliran ayunan. Kajian kebebasan bergerak telah dilakukan dengan meningkatkan jumlah elemen. Grid terbaik adalah yang mempunyai 19170 elemen. Model aliran ayunan adalah fungsi gelombang dan telah berlari untuk 7 kitaran untuk penstabilan pembolehubah. Hasil kajian telah disahkan dengan keputusan teoritis dan konsistensi telah dicapai. Hasil kajian menunjukkan aliran mantap dengan Re yang lebih tinggi mempunyai prestasi pemindahan haba yang lebih baik berbanding dengan Re yang rendah. Aliran ayunan dengan nisbah pemacu yang lebih tinggi mempunyai prestasi pemindahan haba yang lebih baik. Aliran mantap mempunyai prestasi pemindahan haba yang lebih baik berbanding aliran ayunan dengan Re yang sama. Bagaimanapun kenyataan ini tidak dapat disimpulkan dan lebih banyak kerja diperlukan untuk membuktikannya. Cadangan untuk kerja masa depan adalah untuk membangunkan korelasi atau persamaan yang sesuai untuk mengira pekali perpindahan haba untuk aliran silang ayunan ke atas tiub bank.*

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**TABLE OF CONTENTS**

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF APPENDICES

## LIST OF ABBEREVATIONS

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| DR | Drive ratio |
| Re | Reynolds number |
| Ma | Mach number |
| Pr | Prandtl number |
| Nu | Nusselt number |
| Eu | Euler number |
| Ra | Rayleigh number |
| Gr | Grashof number |
| $S_L$ | Longitudinal pitch |
| $S_D$ | Diagonal pitch |
| $S_T$ | Transverse pitch |
| RANS | Reynolds-averaged Navier-Stokes |
| LES | Large eddy simulation |
| DES | Detached eddy simulation |
| DNS | Direct numerical simulation |
| CAD | Computer aided design |

**LIST OF SYMBOL**

| | | |
|---|---|---|
| $\dot{Q}$ | = | Rate of heat transfer |
| $k$ | = | Thermal conductivity / Wave number |
| $A$ | = | Area |
| $h$ | = | Convection heat transfer coefficient |
| $T$ | = | Temperature |
| $\varepsilon$ | = | Effectiveness of heat exchanger |
| $E$ | = | Power |
| $P$ | = | Pressure |
| $\dot{V}$ | = | Volume flow rate |
| $\rho$ | = | Density |
| $m$ | = | Mass |
| $V$ | = | Volume |
| $g$ | = | Gravitational acceleration |
| $\tau$ | = | Shear stress |
| $\gamma_s$ | = | Specific weight |
| $\mu$ | = | Dynamic viscosity |
| $F$ | = | Correction factor |
| $\alpha$ | = | Womersley number / Thermal diffusivity |
| $L$ | = | Length |
| $D$ | = | Diameter |

| | | |
|---|---|---|
| $\nu$ | = | Kinematic viscosity |
| $\omega$ | = | Angular frequency |
| $U$ | = | Velocity / Overall heat transfer coefficient |
| $C_p$ | = | Specific heat |
| $f$ | = | Friction factor / Frequency |
| $\dot{m}$ | = | Mass flow rate |
| $\Delta x$ | = | Thickness |
| $t$ | = | Time period |
| $c$ | = | Speed of sound |
| $\theta$ | = | Phase difference |
| $\lambda$ | = | Wavelength |
| $m'$ | = | Mass flux |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Heat exchangers are instruments that speed up the transfer of thermal energy between two fluids with distinct temperatures while keeping them unmixed (Cengel and Ghajar, 2015). They are used in a wide range of applications such as power production, air-conditioning, chemical processing etc. It works based on the principles of convection (in each fluid) and conduction (between the walls separating the two fluids) mainly. Selection of appropriate heat exchangers is crucial as there are various types of heat transfer applications and each type requires dissimilar hardware, equipment, and configurations.

In order to achieve large heat transfer surface over unit volume, compact heat exchanger is designed specifically. Cross flow is usually found in this kind of heat exchanger, where the two fluids move perpendicular to each other. It is further classified as mixed and unmixed flow. The dissimilarity between mixed and unmixed cross flow is that the fluid is free to move in transverse direction for mixed cross flow while there are plate fins which force the fluid to flow through a particular interfin spacing and prevent it from moving in the transverse direction (like parallel to the tubes) for unmixed cross flow.

Tube bank is the most common type of configuration found in compact heat exchanger. The tubes in a tube bank are usually arranged either in-line or staggered in the direction of flow. Flow through the tubes can be analyzed by considering flow through a single tube, and multiplying the results by number of tubes. However, this is not the case for flow over the tubes because the tubes will affect the flow pattern and turbulence level downstream, and thus heat transfer to or from them.

Thermoacoustic engine is a device that works in similar way like a heat exchanger. Instead of using fan or pump to drive the fluid forward, it works by using acoustic power to pump heat from a low-temperature sink to a high temperature sink. One of the uniqueness in a thermoacoustic engine is that it doesn't consist of moving parts therefore it's relatively cheap to produce. Oscillatory flow mode is often found in a thermoacoustic engine because it employs acoustic power which is power transmitted by sound wave. Oscillatory flow is a very interesting topic and there isn't enough research done on it especially for tube banks.

In this project, steady and oscillatory cross flow over tube banks will be studied using Computational Fluid Dynamics (CFD) software such as Ansys Fluent. Using CFD will make the analysis much easier by performing numerical simulation and eliminating the need of experimenting without compromising the accuracy and integrity of results.

The heat transfer characteristics for cross flows over tube banks are of important practical interest (Bhutta et al., 2012), which also represents an idealization of many other industrially important processes (Mandhani et al., 2002). Therefore, it is very important to study the characteristics of fluid flow and heat transfer of cross flows over tube banks, which could lead to a better design of heat exchanger (Kim, 2013).

## 1.2 Problem statement

The thermodynamics performances like heat transfer are exceptionally significant when designing or selecting the right heat exchanger. One of the criteria is the flow of fluids over the tube banks. There are many kinds of flows over the tube banks, however, only steady one-directional and oscillatory cross flows are focused in this study. In simple terms, steady one directional cross flow implies that the fluids only flow in one direction (transverse motion is acceptable). While on the other hand, oscillatory cross flow works almost like the flow mentioned before, however, it flows in oscillatory manners which mean it changes the direction over time (reverse motion included). For instance, the oscillatory flow cases can be found if the tube bank is placed in situation like ocean flow, blood flow, and thermoacoustic engine.

The fluid dynamics and heat transfer across the tube banks is well-established particularly for a steady one-directional flow. The problem is that after reviewing several literatures regarding the subject matter, it is apparent that the research done on oscillatory cross flow over tube bank is limited and scarce. It is profound that the research on tube banks for now couldn't fully represent the whole ideal situation in which the flows could be more than just one-directional.

Therefore in this project, the one-directional cross flow over the tube banks will be studied, simulated and set as benchmark. For further analysis, oscillatory cross flow over the tube banks will be compared with the aforementioned case.

## 1.3 Objective

The objectives of this project are as follow:

1. To use CFD to model cross flow over tube banks.
2. To compare fluid flow characteristics between steady one-directional and oscillatory cross flows.
3. To compare heat transfer characteristics between steady one-directional and oscillatory cross flows.

## 1.4 Scope of project

The scopes of this project are:

1. Only CFD simulation method is used for this project. Experiment method is out of consideration.
2. Only focus on cross flow over tube bank instead of the whole performance of tube bundles with shell side as in a shell-and-tube heat exchangers.
3. CFD analysis will be conducted in 2D instead of 3D.
4. CFD simulation will focus on steady one directional and oscillatory cross flow.
5. Only consider the tube banks with base surfaces (no fins).
6. Only focus on the fluid which flows over tube banks instead of the fluid inside the tubes.

# CHAPTER 2

# LITERATURE REVIEW

## 2.0 Introduction

This chapter will discuss in details on the data and information of research topic which is CFD investigation of cross flow over tube banks. To be specific, some of the related terms and researches such as heat transfer modes and their characteristics, numerical simulation, fluid mechanics, tube bank configurations, flow criteria, etc. will be discussed elaborately. Research gap about cross flows over tube banks will be investigated.

## 2.1 Heat transfer

According to Cengel and Cimbala (2014), heat transfer is the discipline of thermal engineering that deals with determination of the rate of energy that can be transferred between physical systems to another as an outcome of temperature difference. Fundamental principle of heat transfer is the existence of temperature difference. It acts as a driving force for heat transfer just like potential difference is the driving force for electricity. Besides, the magnitude of temperature gradient influences the rate of heat transfer in specific direction, usually from higher temperature to low temperature according to second law of thermodynamics. The larger the temperature gradient, the higher the rate of heat transfer. However as the time goes, thermal equilibrium is achieved and the temperatures are uniform due to the gradual decay of temperature difference without external source of energy.

There are a few fundamental modes for the heat to be transferred, and they are conduction, convection, and radiation. Presence of temperature difference is a requirement for all modes mentioned.

### 2.1.1 Conduction

Conduction is the transfer of internal energy from particles with more energy to the adjacent particles with less energy of a substance as a result of interactions between the particles via direct contact. Conduction can take place not only in solids as everyone perceived, but in liquids, and gases as well.

In solids, conduction is due to the combination of collisions and vibrations of the molecules in a lattice and the energy transport by free electrons. While in liquids and gases, it is due to the collisions and diffusion of the molecules during their random motion. The rate of heat conduction relies on the temperature difference, material, thickness of the medium. Figure 2.1 shows an illustration of conductive heat transfer through a plane wall.

Fourier's law of heat conduction is defined as in Eq. (2.1):

$$\dot{Q} = -kA\frac{dT}{dx} \tag{2.1}$$

where $\dot{Q}$ is rate of heat conduction (SI units: W), $k$ is thermal conductivity of material (SI units: W/m·K), $A$ is heat transfer area (SI units: $m^2$), $dT/dx$ is temperature gradient (SI units: K/m).