Faculty of Mechanical Engineering

INVESTIGATION OF ONE-DIRECTIONAL AND BI-DIRECTIONAL FLOWS ACROSS STAGGERED TUBE BANKS HEAT EXCHANGER

Nurjannah binti Hasbullah

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NURJANNAH BINTI HASBULLAH

A thesis submitted
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DECLARATION

I declare that this thesis entitled "Investigation of One-directional and Bi-directional Flows across Staggered Tube Banks Heat Exchanger" 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 : ....

Name : Nurjannah binti Hasbullah

Date : 14/6/2022

APPROVAL

I hereby declare that I have read this thesis and in my own opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : ……………………………………………..

Supervisor's Name : Dr. Fatimah Al-Zahrah binti Mohd Sa'at

Date : 14/6/2022

DEDICATION

I dedicate this thesis to my dearest parents and also my family, who have been my source of inspiration and gave me strength when I thought of giving up, who continually provide their moral, spiritual, emotional and financial supports.

ABSTRACT

One-directional and bi-directional flow conditions are different in terms of the direction of fluid flows. One-directional flow condition is when the fluid flows only in one direction. Meanwhile, bi-directional flow condition happens when the fluid flows in back and forth directions and this has been found in applications such as thermoacoustics. Thermoacoustics offer green technology for refrigeration and power cycles. The technology is appealing, but the lack of understanding on fluid dynamics and heat transfer behaviours of flow inside the system lead to the ambiguous use of equations from the well-known one-directional flow during the design stage and the impact of such estimation becomes evident as the flow in the real system becomes more complex. For this reason, experimental investigations that are supplemented by computational fluid dynamics modelling results are carried out with a focus on the heat exchanger. A staggered tube-banks heat exchanger was tested. A thermoacoustic's standing wave rig with different type of flow inducers is used to create the one-directional and the bi-directional flows for the experiments. Results of velocity and temperature were recorded at the upstream and downstream locations of the staggered tube banks heat exchanger. The frequency of the bi-directional flow was set based on the resonance frequency of 14.2 Hz. Results indicate that temperature and velocity changes with respect to the change of flow amplitude are different between the one-directional and bi-directional flow conditions and the differences are in the range of 77 percent and 59.5 percent, respectively. A two-dimensional model of staggered tube banks heat exchanger is solved using a commercial software Ansys Fluent 16.0. The flow conditions were solved for the range of Reynolds between 270 and 1700 using SST k-ω turbulence models and the temperature contour, vorticity contour and the velocity vectors were discussed based on the results of the validated models. A similar trend of Nusselt number changes with the change of Reynolds number is seen between the experimental and numerical works of the one-directional flow and the bi-directional flow conditions, with errors of amplitude expected to be due to the limitations of experimental apparatus as well as the simplifications and assumptions made for the computational fluid dynamics works. Nevertheless, most recorded differences fell within the experimental uncertainty values of ± 2.8 to ± 5.8. The computational fluid dynamics models provided insight into the visualization of flow in area that could not be seen experimentally. Evidently, the bi-directional flow conditions are different compared to the one-directional flow condition by 65.85 percent at Reynolds number of 1300. Therefore, the use of the well-established one-directional flow equation on bi-directional flow conditions should be avoided should an accurate result is needed in the design stage of the future thermoacoustic energy systems.

KAJIAN ALIRAN SATU-ARAH DAN DUA-ARAH MERENTASI BANK TIUB TIDAK SERENTAK PENUKAR HABA

ABSTRAK

Keadaan aliran satu arah dan dua arah adalah berbeza dari segi arah aliran bendalir. Keadaan aliran satu arah berlaku apabila bendalir mengalir dalam satu arah. Sementara keadaan aliran dwi-arah berlaku apabila bendalir mengalir ke hadapan dan ke belakang dalam dua arah dan telah ditemui dalam aplikasi seperti termoakustik. Termoakustik menawarkan teknologi hijau untuk kitaran penyejukan dan kuasa. Teknologi ini menarik, tetapi kekurangan pemahaman tentang dinamik bendalir dan gelagat pemindahan haba di dalam sistem membawa kepada penggunaan kaedah anggaran dengan menggunaan persamaan yang terkenal daripada aliran satu arah semasa peringkat reka bentuk sistem dan kesan anggaran tersebut menjadi jelas apabila aliran dalam sistem sebenar menjadi lebih rumit. Atas sebab ini, penyiasatan ujikaji yang disokong dengan kajian pemodelan dinamik bendalir dijalankan dengan fokus pada penukar haba. Penukar haba bank tiub tidak serentak telah diuji. Alatan ujikaji termoakustik dengan gelombang berdiri serta jenis pengaruh aliran yang berbeza digunakan untuk mencipta aliran satu arah dan dua arah untuk ujikaji. Keputusan halaju dan suhu telah direkodkan di lokasi hulu dan hilir penukar haba bank tiub tidak serentak. Kekerapan aliran dua arah ditetapkan berdasarkan frekuensi salunan 14.2 Hz. Keputusan menunjukkan bahawa perubahan suhu dan halaju dengan peningkatan amplitud aliran satu arah dan dua arah adalah berbeza dan perbezaannya adalah masing-masing pada julat 77 peratus dan 59.5 peratus. Model dua dimensi penukar haba bank tiub tidak serentak dibangunkan dalam perisian komersial Ansys Fluent 16.0. Keadaan aliran telah diselesaikan untuk julat nombor Reynolds di antara 270 dan 1700 dengan menggunakan model SST k-ω dan kontur suhu, kontur vorteks dan vektor halaju telah dibincangkan berdasarkan keputusan model yang telah disahkan. Corak perubahan nombor Nusselt berdasarkan perubahan nombor Reynolds dari ujikaji dan model simulasi adalah sama dengan ralat yang dijangka disebabkan oleh batasan radas ujikaji serta pemudahan, dan andaian yang dibuat oleh simulasi CFD. Namun begitu, kebanyakan perbezaan yang direkodkan berada dalam nilai ketidakpastian eksperimen di antara ± 2.8 hingga ± 5.8. Model CFD memberikan gambaran tentang aliran di kawasan yang tidak dapat dilihat secara eksperimen. Jelas sekali, keadaan aliran dua arah adalah berbeza berbanding dengan keadaan aliran satu arah dengan 65.84 peratus pada nombor Reynolds 1300. Oleh itu, penggunaan persamaan mantap dari aliran satu arah di dalam analisis aliran dua arah harus dielakkan sekiranya keputusan yang tepat diperlukan dalam peringkat reka bentuk sistem tenaga termoakustik pada masa hadapan.

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

2D	-	Two-dimensional
CFC	-	Chlorofluorocarbon
CFD	-	Computational Fluid Dynamics
DR	-	Drive ratio
FE	-	Finite Element
FEA	-	Finite Element Analysis
HFC	-	Hydrofluorocarbon
HVAC	-	Heating Ventilation Air Conditioning
HX	-	Heat Exchanger
LMTD	-	Log Mean Temperature Difference
NTU		Number of Heat Transfer Unit
PIV	-	Particle Image Velocimetry
SST	-	Shear Stress Transport
UDF	-	User Defined Function
λ	-	Wavelength
c	-	Speed of sound
f	-	Frequency
S_L	-	Horizontal length
S_T	-	Transverse length
S_D	-	Diagonal length
D	-	Diameter of tubes
V_{in}	-	Inlet velocity
V_{out}	-	Outlet velocity

T_{in}	-	Inlet temperature
T_{out}	-	Outlet temperature
T_s	-	Surface temperature
T_o	-	Mean temperature
P_{air}	-	Density of air
Cp_{air}	-	Specific heat capacity
λ_t	-	Thermal conductivity
μ_{air}	-	Dynamic viscosity
α	-	Diffusivity
y^+	-	Location of the nearest node from the wall
Re	-	Reynolds number
Nu	-	Nusselt number
Pr	-	Prandtl number
Z	-	Tidal displacement
$\mathrm{W_o}$		Womersly number
$\mathrm{L_c}$		Characteristic length
R	-	Tube radius
υ	-	Kinematic viscosity
ω	-	Angular frequency
U_{max}	-	Maximum velocity amplitude
x_1	-	Inlet location
x_2	-	Outlet location
m'	-	Mass flux
P	-	Oscillating pressure
P_a	-	Pressure amplitude
P_m	-	Mean pressure
k	-	Wave number
t	-	Time
θ	-	Phase difference
Φ	-	Phase
$\bar{x}$	-	Mean value
n	-	Repeated numbers

A	-	Area
L	-	Length
W	-	Width
$\dot{Q}$	-	Rate of heat transfer
h	-	Heat transfer coefficient
$\dot{m}$	-	Mass flow rate
U	-	Uncertainty
s	-	Precision uncertainty
b	-	Systematic uncertainty
σ	-	Standard deviation

LIST OF APPENDICES

LIST OF PUBLICATIONS

Nurjannah Hasbullah, Fatimah Al-Zahrah Mohd. Saat, Fadhilah Shikh Anuar, Dahlia Johari and Mohamad Firdaus Sukri. Temperature and Velocity Changes across Tube Banks in One-directional and Bi-directional Flow Conditions. *Evergreen Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, Vol. 08, Issue 02, pp.428-437.

Nurjannah Hasbullah, Fatimah Al Zahrah Mohd Saat, Fadhilah Shikh Anuar, Mohamad Firdaus Sukri and Patcharin Saechan. Experimental and numerical studies of one-directional and bi-directional flow conditions across tube banks heat exchanger. *Thermal Science Engineering Progress*, Vol. 28, pp. 101176.

Nurjannah Hasbullah, Fatimah Al Zahrah Mohd Saat, Fadhilah Shikh Anuar, Mohamad Firdaus Sukri, Zaid Akop and Zainuddin Abdul Manan (2021, November 23). *Uncertainty analysis of thermal fluid measurements for bi-directional flow condition across tube banks* [Paper presentation] ICESEAM 2021: Melaka, Malaysia.

Nurjannah Hasbullah, Fatimah Al Zahrah Mohd Saat, Fadhilah Shikh Anuar, Mohamad Firdaus Sukri, Mohd Zaid Akop, Zainuddin Abdul Manan (2021). *Experimental study on the performance of one-directional and bi-directional flow conditions across in-line tube banks heat exchanger*. Manuscript submitted for publication.

CHAPTER 1

INTRODUCTION

1.1 Background of study

Heat exchangers are devices that are used at various temperatures for the purposes of transferring heat between two or more fluid sources. Heat exchangers are commonly used in applications such as power generation, chemical processing, electronics cooling, air conditioning, refrigeration and automotive industry (Kuruneru et al., 2020). Heat exchanger is a system involving the heat exchange between two fluids with two different temperatures; the high temperature fluid usually known as a hot fluid and the low temperature fluid commonly referred as the cold fluid. The heat transfer process between the two fluids takes place in the heat exchangers (Afonso et al., 2003). The efficiency of the heat transfer process varies with the change of flow conditions and directions. Shell-and-tube heat exchanger is one of the types of heat exchangers that consist of a collection of tubes containing fluid that either be heated or refrigerated (Raju et al., 2014). The other fluid runs over the heated or cooled pipe, so that it can either supply the heat or absorb the heat. A package of tubes is called a bundle of tubes and may consist of many types of tubes, such as regular and longitudinally finished. Typically, the heat exchangers for shells and tubes are used for high pressure applications. This is because the heat exchangers that consist the shell and the tube are robust because of their shape (T'Joen et al., 2009). In addition to the shape and dimension of the heat exchanger, the direction of fluid flow also plays role on the rate of heat transfer between the fluids. In most situations, the fluid flows in one direction only. Nonetheless, in some cases, the fluid flows not in the normal steady one-directional form but in different directions such as the flow of blood, oscillatory flow in thermoacoustic engine or cooler and the flow in an ocean (Yang et al., 2017). The oscillatory flow of blood flow, thermoacoustic energy system and the ocean flow can be defined as a bi-directional flow as the fluid flows forth and back in two main directions. Nevertheless, it is found that the basic understanding of heat transfer in flows other than steady one-directional flow condition is uncommon. Investigation is needed and this requires comprehensive methods which will be able to reveal differences or similarity of behaviours between the two different type of flow conditions; the bi-directional flow condition and the usual one-directional condition.

The bi-directional flow condition can be found in the relatively new green technology known as thermoacoustic technology. The technology can be used for power cycle as well as refrigeration cycle. In this modern world, refrigeration plays a central role as it is needed in almost all aspects of technology (Wang et al., 2018). The process of cooling occurs through the process of compression of vapour, which uses a specific coolant. After its introduction in the early 19th century, the refrigeration system underwent much developments. Nevertheless, the traditional refrigeration device poses a significant threat to the atmosphere through the production of green-house gases that deplete ozone (Hunt and Raman, 2017). To achieve the appropriate temperature, blends of carbon, hydrogen, fluorine, and chlorine are mixed in different ratios. This also has the potential to cause global warming. In addition, the vapour compression system entails high cost of electricity. After determining these harmful impacts, efforts are made to start moving over from standard refrigeration on an ongoing basis. In general, resources must be efficiently utilized, which may be accomplished, among other things, by several technological advancements (World Energy Council, 2018). Thermoacoustic technology is one developing technology with this potential. This technique may be used with sound waves and heat as inputs inside a pressured environment to generate either power (engine) or cooling effect (refrigerator). This system also has a number of advantages, such as the fact that it operates without moving parts and uses non-harmful chemicals as a working fluid, making it a potentially appealing technology. Thermoacoustic cooling is a viable substitute, as it offers the preferred cooling level without the need for any harmful substances (Leclaire and Heldebrant, 2018). The bi-directional flow conditions of thermoacoustics is less understood (Hasbullah et al., 2021). Figure 1.1 shows the comparison of fluid direction between the oscillatory flow of thermoacoustics, or also known as bi-directional flow, and the unidirectional flow that has been widely used in many conventional systems. Bi-directional flow is a condition where the fluid flows back and forth in the system while in unidirectional flow the fluid flows only in one direction.

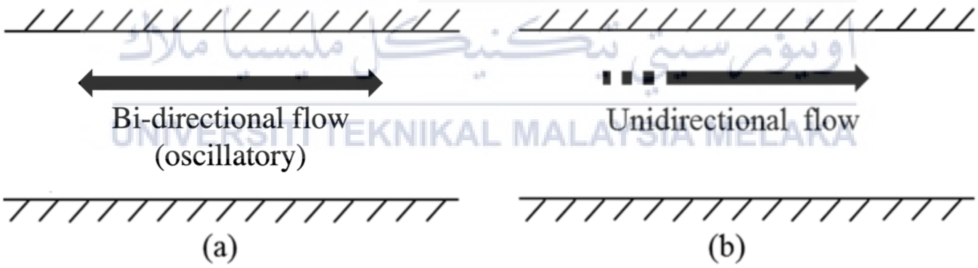

Figure 1.1: Schematic diagram of fluid direction in (a) bi-directional flow and (b) unidirectional flow

Since technological development must focus not only on the performance of the system but also on the technological impact on the environment, thermoacoustics which provide green technology for at least two major applications; cooling and power generation equipment, are favourable. Figure 1.2 shows a simple thermoacoustic mechanism.

Basically, the thermoacoustic system consists of a loudspeaker as an acoustic driver, a tube banks heat exchanger and a resonator as the main body of the system. In thermoacoustics, the heat exchangers as well as the stack/regenerator that are used in the system are also referred to as porous media due to the feature of porous structure with micro and mini sizes pores (Saat, 2013). A more complicated arrangements can be used to obtain better efficiency but the simple mechanism, as shown in Figure 1.2, should be sufficient to create the thermoacoustic environment.

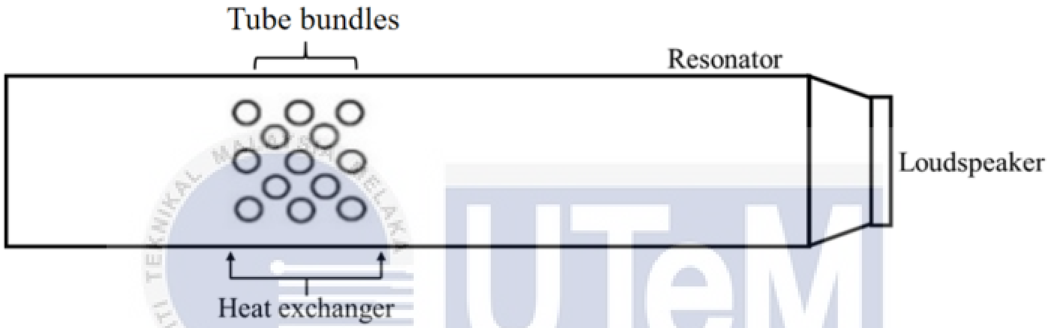

Figure 1.2: Simple schematic diagram of thermoacoustic systems

The acoustic wave contains variations of pressure and volume flow rate that oscillates depending on the frequency of the flow. The proper phasing between the acoustically induced fluid displacement and its compression or expansion, combined with heat transfer process would result in the application of Stirling-like thermodynamic cycles which are of engineering problems significance. The use of harmless refrigerants such as hydrogen, helium or some other inert gas as a working medium is environmentally friendly and provide benefits to the technology. The thermoacoustic cooling system provides additional advantages of lower operating costs because there are no moving parts and thus there is no lubrication system requirement. Due to the promising feature of thermoacoustic technology, the oscillatory flow condition of thermoacoustics has been selected to represent