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STREAMING IN OSCILLATORY FLOW THROUGH POROUS CHANNELS IN THERMOACOUSTICS

NUR AFIQAH AINA BINTI ZAIHAM

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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NUR AFIQAH AINA BINTI ZAIHAM

A thesis submitted in fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

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2025

DECLARATION

I declare that this thesis entitled “Streaming in Oscillatory Flow Through Porous Channels in Thermoacoustics” 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 : NUR AFIQAH AINA BINTI ZAIHAM

Date : 09 SEPTEMBER 2025

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APPROVAL

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

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Date : 09 SEPTEMBER 2025

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DEDICATION

I dedicate this work to my parents, who taught me the value of perseverance, to my loved one, who has been my constant source of strength and to my friends, who never stopped believing in me.

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ABSTRACT

Streaming in oscillatory flow of the alternative green technology known as thermoacoustics remains relatively less understood. The thermodynamic cycle in the system is driven by the oscillatory flow of the acoustic waves, understanding the nature of streaming, particularly within the porous structure of the system is crucial. Since the current study does not include a heat exchanger to generate a temperature gradient, it cannot directly be used as a complete thermoacoustic system. Instead, this design choice aligns with the primary aim of the study, which was to investigate the flow dynamics and acoustic streaming within an oscillatory flow field in a thermoacoustic system without thermal effect. This study was done using a parallel-plate porous channel operating under standing-wave conditions at a quarter wavelength. Both experimental and computational fluid dynamics (CFD) approaches were used. The experimental data, including the velocity, pressure and wall displacement were recorded under a resonance frequency of 23.6 Hz. The flow was maintained at room temperature and atmospheric pressure, with drive ratios ranging from 0.64% to 3.01%. These measurements were then incorporated into CFD simulations to provide deeper insight into complex flow physics. The two-dimensional (2D) CFD model was solved for minimum, medium and maximum flow conditions using the Shear Stress Transport (SST) k-ω turbulence model. Comparisons and discussions were made based on the data from the experiment, CFD and one-dimensional linear thermoacoustic theory. Results showed that the discrepancies between experimental and numerical results were slightly larger, possibly due to vibration effects during testing. To address this, a dynamic mesh was applied to simulate wall movement. This adjustment results in a slightly improved correlation with experimental data, especially for peak velocity at the downstream location. Further analysis of vortex structures over 20 phases of a flow cycle was carried out. The results show that under moving wall conditions, vortices shed further and extended longer into the open area, with a 12.40% deviation from the non-moving wall case at high acoustic amplitudes. The observation of flow streaming was made based on the progress of velocity profiles over time. In addition, the CFD model was extended with the Ffowcs-Williams and Hawkings (FW-H) acoustic model to analyse the sound pressure level (SPL) at three receivers positioned at the inlet, mid-channel and outlet of the computational domain. The highest SPL was recorded at the mid-channel, attributed to strong interactions between acoustic waves and solid boundaries, with the acoustic source positioned at the inlet. A parametric study using helium as the working fluid was also conducted to explore the effect of fluid properties on flow behavior and streaming. The simulations were conducted under the same drive ratios as those used for air. Results showed that Rayleigh streaming in helium is significantly weaker than in air, with a reduction in streaming intensity of approximately 34.17%, while Schlichting streaming appeared negligible. These findings were further strengthened by comparisons with existing literature, reinforcing the validity of the proposed methodology. Overall, this study provides new insights into nonlinear flow behavior in thermoacoustics. The findings enhance predictive modelling of oscillatory flows in porous channels and support the design of more efficient thermoacoustic systems for sustainable cooling, waste-heat recovery and renewable energy conversion.

PENJURUSAN DALAM ALIRAN AYUNAN MELALUI SALURAN BERLIANG DALAM TERMOAKUSTIK

ABSTRAK

Penjurusan dalam aliran ayunan bagi teknologi hijau alternatif termoakustik masih kurang difahami. Sistem ini dipacu oleh aliran ayunan gelombang akustik, maka pemahaman terhadap sifat penjurusan, khususnya berhampiran struktur berliang, amat penting untuk memastikan prestasi optimum. Kajian ini tidak melibatkan penukar haba untuk menjana kecerunan suhu, oleh itu ia bukan sistem termoakustik lengkap, sebaliknya menumpukan pada penyelidikan dinamik aliran dan penjurusan akustik tanpa kesan haba. Kajian dijalankan menggunakan saluran berliang plat selari yang beroperasi di bawah gelombang pegun dengan konfigurasi suku panjang gelombang. Pendekatan eksperimen dan CFD digunakan, di mana data halaju aliran, tekanan dan pergerakan dinding direkodkan pada frekuensi resonan 23.6 Hz dalam keadaan suhu bilik dan tekanan atmosfera, dengan julat nisbah pacuan 0.64%–3.01%. Data ini seterusnya digunakan dalam simulasi CFD untuk memahami tingkah laku fizikal aliran yang kompleks. Model CFD dua dimensi (2D) diselesaikan bagi keadaan aliran minimum, sederhana dan maksimum menggunakan model pergolakan SST k-ω. Perbandingan dibuat dengan data eksperimen dan teori linear satu dimensi. Hasil menunjukkan terdapat sedikit perbezaan antara eksperimen dan simulasi yang berkemungkinan disebabkan oleh kesan getaran. Bagi menangani isu ini, jejaring dinamik digunakan untuk mensimulasikan pergerakan dinding, menghasilkan korelasi lebih baik dengan data eksperimen, khususnya pada halaju puncak di lokasi hujung. Analisis pusaran bagi 20 fasa kitaran aliran mendapati dinding bergerak menghasilkan pusaran yang memanjang 12.40% lebih jauh ke arah kawasan terbuka berbanding kes dinding statik pada amplitud tinggi. Model CFD turut diperluas dengan model akustik Ffowcs-Williams dan Hawkings (FW-H) untuk menganalisis tahap tekanan bunyi (SPL) pada penerima di bahagian masuk, tengah dan keluar saluran. SPL tertinggi diperoleh di bahagian tengah saluran, disebabkan interaksi kuat antara gelombang akustik dan dinding pepejal, dengan sumber akustik terletak di bahagian masuk. Selain itu, kajian parametrik menggunakan helium sebagai bendalir kerja dijalankan bagi menilai kesan sifat bendalir. Simulasi dengan nisbah pacuan yang sama seperti udara menunjukkan penjurusan Rayleigh dalam helium jauh lebih lemah, dengan pengurangan sekitar 34.17%, manakala penjurusan Schlichting hampir tiada. Penemuan ini konsisten dengan kajian terdahulu, sekali gus mengesahkan pendekatan kajian. Secara keseluruhan, kajian ini memberikan pandangan baharu mengenai tingkah laku aliran bukan linear dalam termoakustik, meningkatkan pemodelan ramalan aliran ayunan dalam saluran berliang serta menyokong pembangunan sistem termoakustik yang lebih cekap untuk penyejukan mampan, pemulihan haba buangan dan penukaran tenaga boleh diperbaharui.

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LIST OF ABBREVIATIONS

CFC	-	chlorofluorocarbon
CFD	-	Computational fluid dynamics
DC	-	Direct current
FDM	-	Finite Difference Method
FEM	-	Finite Element Method
FFT	-	Fast Fourier Transform
FVM	-	Finite Volume Method
FW-H	-	Ffowcs-Williams and Hawkings
HFC	-	hydrofluorocarbon
PISO	-	Pressure-Implicit with Splitting Operators
PIV	-	Particle Image Velocimetry
RANS	-	Reynolds Averaged Navier-Stokes
SPL	-	Sound pressure level
SST	-	Shear Stress Transport
UDF	-	User Defined Function
VCR	-	vapor-compression refrigeration

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LIST OF SYMBOLS

2D	-	two-dimensional
3D	-	three-dimensional
c	-	Speed of sound
P	-	pressure
ρ	-	density
F_R	-	resonant frequency
L	-	length of resonator
T	-	absolute temperature
R	-	gas constant
γ	-	Adiabatic gas constant
Pr	-	Prandtl number
ν	-	kinematic viscosity
α	-	thermal diffusivity
C_p	-	specific heat
μ	-	dynamic viscosity
k	-	thermal conductivity
ω	-	angular frequency
y_0	-	Plate spacing
$\delta\nu$	-	viscous penetration depth
δk	-	thermal penetration depth
λ	-	wavelength
dB	-	decibels

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Hz	-	Hertz
k-ε	-	k-epsilon
k-ω	-	k-omega
Vpp	-	peak-to-peak voltage
d	-	thickness
D	-	Plate spacing
D	-	Tube diameter
v	-	velocity
DR	-	Drive ratio
Pa	-	Pascals
Pm	-	mean pressure
$\dot{m}$	-	mass flow rate
m'	-	mass flux
k_w	-	wave number
Re	-	Reynold number
Δ	-	Wall displacement
θ	-	phase angle
Ø	-	Phase of cycle
I	-	turbulent intensity
l	-	turbulent length
d_h	-	hydraulic diameter
P_{RMS}	-	root mean square
S(x)	-	Swirling vector

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LIST OF PUBLICATIONS

The following is the publication related to the work presented in this thesis:

Zaiham, N. A. A., Saat, F. A. Z. M., Xuan, Y. Y., Anuar, F. S. and Saechan, P., 2024. The Effect of Vibration on Flow Inside a Standing Wave Thermoacoustic Condition. *International Journal of Integrated Engineering*, 16 (2), pp. 348–362.

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CHAPTER 1

INTRODUCTION

This chapter introduces a brief background of the study focusing on the streaming phenomenon in oscillatory flow within thermoacoustic devices. The problem statement, research objectives and scope of the study are also explained.

1.1 Background

Pollution and global warming threats should no longer be taken lightly. Addressing these worldwide environmental issues is one of the most serious challenges for society in the twenty-first century (Laine et al. 2023). The energy supply sector is primarily responsible for the excessive use of fossil fuels, resulting in the release of significant amounts of greenhouse gases. This emission further leads to the release of unused waste heat, worsening the current global energy crisis and disrupting the fragile ecological balance (Chen et al. 2023). Given the worsening concern surrounding these matters, the world is seriously implementing plans on strengthening green technologies and the use of renewable energy sources as the means to address the ever-growing demands for energy worldwide. In recent years, numerous renewable energy technologies have been proposed, offering the ability to utilize low-grade heat and naturally replenish themselves at a rate that meets energy demands.

With promising features, the development of green technologies, such as thermoacoustics, shows great potential as a replacement for conventional refrigeration as they use inert gases as their working fluid rather than refrigerants (Luo et al. 2023). This is

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primarily owing to the excellent qualities of dependability and environmental friendliness, which allow the inert gas to deliver worldwide energy services while leaving a tiny carbon footprint (Bhatti et al. 2023). According to Timmer et al. (2018), the effective operation of thermoacoustic devices necessitates a thorough comprehension in flow dynamics, transient phenomena, and the conversion of acoustic waves into energy, as this expertise guarantees the sustainability of thermoacoustic effects. Another key requirement for effective thermoacoustic devices is reliance upon the oscillatory motion of the working fluid. In this state, the compressible fluid moves back and forth through the porous structures, creating thermodynamic cycles that generate energy based on thermoacoustic principles. Luo et al. (2023) have determined that this characteristic of the flow is ideal for both the refrigeration and the power production applications, as it facilitates the thermodynamic cycle for energy conversion.

A standing-wave thermoacoustic system typically consists of a resonator tube, a porous stack, an acoustic driver and two heat exchangers positioned at the hot and cold ends, as shown in Figure 1.1. Kajurek and Rusowic (2021) mentioned that the acoustic driver generates an acoustic wave that propagates through the gaseous phase, thereby facilitating heat transfer, compression, and expansion processes upon its interaction with the solid surface of the stack plates. This will eventually results in a temperature disparity between the two ends of the stack. This is the reason the stack is referred to as the "core" of a thermoacoustic system, as it is the location where all thermoacoustic processes, comprising of the expansion, the compression and heat transfer, take place (Almukhtar Allafi et al. 2021). Another appealing feature of this simple alternative refrigeration system is the use of