Faculty of Mechanical Engineering

NUMERICAL INVESTIGATION OF FLOW CHARACTERISTICS OF AN OSCILLATORY FLOW ACROSS A THERMOACOUSTIC STACK

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DECLARATION

I declare that this thesis entitled "Numerical Investigation of Flow Characteristics of an Oscillatory Flow Across a Thermoacoustic Stack" 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	:	…………………………….
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Date	:	…………………………….

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

Date : …………………………….

DEDICATION

I dedicate this thesis to my beloved parent and also my family, who have been my source of inspiration and gave me strength when I though of giving up, who continually provide their moral, spiritual, emotional and financial support.

ABSTRACT

Thermoacoustic system uses green technology to convert heat into electrical power or vice versa. The technology is attractive but the lack of understanding about fluid dynamics behavior of flow inside the system leads to the challenging issue in improving the system's performance. Therefore, fundamental study of fluid dynamics in the complex thermoacoustic flow condition is needed. In this study, fluid dynamics investigations of an oscillatory flow across internal structure of a thermoacoustic system were carried out. Two dimensional CFD models of flow across structure known as "stack" inside thermoacoustic systems were solved using ANSYS CFD. The models were solved using laminar, Transition SST and SST k-ω turbulence models. The investigation covered drive ratios from 0.3 percent to 3.0 percent which corresponded to Stokes Reynolds number of 59 to 1722. A new investigation of the effect of flow frequency was also reported. The frequencies of flow was set at 13.1 Hz and 23.1 Hz. The CFD models were validated using experimental results. An experimental standing wave rig was developed and velocity data was measured and then used to validate the CFD models. The results of the CFD model agreed with experimental data with the errors ranging between 0.36 to 7.69 percent. Due to the limitation of the experimental rig, cases with drive ratio lower than 0.8 percent and higher than 1.6 percent were verified using theoretical solution. A good match was found between the CFD results and theoretical solution especially at low Reynolds number. Deviation between CFD results and theoretical predictions at high Reynolds number was discussed. Results were discussed based on velocity profiles and vorticity contour of flow within and around the "stack". At 13.1 Hz, turbulence was found to start at a Reynolds number as low as 163. The start of turbulence was delayed to a Reynolds number of 308 as the frequency was increased to 23.1 Hz. The investigation of vortex shedding flow phenomena revealed nine patterns of vortex shedding evolution for both flow frequencies. The vortex that sheds at the end of structure will come back into the channel of the structure as the flow reversed. As a result, the entry length for this oscillatory flow was found to be better predicted using the well-established entry length equation for turbulence one-dimensional flow condition even if the oscillatory flow was laminar. Comparison between the current study and published works regarding the ratio of the channel height to the boundary layer thickness (D/δ_v) was also presented to strengthen the validity of the results of current study. The comprehensive fluid dynamics analysis reported in this study are expected to be beneficial for system that works with oscillatory flow condition especially the thermoacoustic systems.

ABSTRAK

Sistem termoakustik menggunapakai teknologi hijau untuk menukar haba kepada kuasa elektrik dan sebaliknya. Teknologi tersebut menarik tetapi pemahaman yang kurang terhadap kelakuan dinamik bendalir dalam aliran sistem mendorong kepada cabaran untuk menambahbaik prestasi sistem tersebut. Maka kajian asas terhadap dinamik aliran dalam keadaan aliran termoakustik yang kompleks diperlukan. Dalam kajian ini, model CFD dua dimensi untuk aliran merentasi struktur "stack" dalam sistem termoakustik telah diselesaikan menggunakan ANSYS CFD. Model tersebut telah diselesaikan menggunakan model laminar, model pergolakan Transition SST dan SST k-ω. Kajian ini merangkumi nisbah penggerak dalam julat 0.3 peratus sehingga 3.0 peratus yang bersamaan dengan nombor Stokes Reynolds 59 sehingga 1722. Kajian baru berkaitan frekuensi aliran telah dilaporkan. Frekuensi aliran adalah dari 13.1 Hz dan 23.1 Hz. Model CFD telah disahkan menggunakan data eksperimen. Sebuah rig eksperimen gelombang berdiri telah dibangunkan dan data halaju telah diukur dan digunakan untuk mengesahkan model CFD tersebut. Perbandingan keputusan CFD dan eksperimen adalah baik dengan peratus kesilapan 0.36 peratus sehingga 7.69 peratus. Disebabkan kekangan rig ujikaji, model dengan nisbah penggerak rendah daripada 0.8 peratus dan tinggi daripada 1.6 peratus hanya dapat disahkan menggunakan teori. Padanan yang baik telah diperolehi antara keputusan CFD dan penyelesaian teori pada nombor Reynolds yang rendah. Sisihan nilai di antara keputusan CFD dan penyelesaian teori pada nombor Reynolds yang tinggi turut dibincangkan. Data yang diperolehi telah dibincangkan dari segi profil halaju dan aliran kontur vortisiti di kawasan dalam dan sekitar "stack". Pada 13.1 Hz, pergolakan telah dikesan bermula pada nombor Reynolds serendah 163. Permulaan pergolakan telah tertangguh ke nombor Reynolds 308 apabila frekuensi meningkat ke 23.1 Hz. Kajian terhadap fenomena aliran tumpahan vorteks telah menunjukkan sembilan corak evolusi tumpahan vorteks pada kedua-dua frekuensi. Vorteks yang tertumpah pada hujung struktur akan kembali ke dalam saluran apabila aliran berpatah balik. Sebagai hasilnya, panjang masukan aliran ayunan ditemui lebih sesuai diramalkan menggunakan persamaan panjang masukan sedia ada untuk keadaan pergolakan satu dimensi, walaupun aliran ayunan tersebut berada dalam keadaan laminar. Perbandingan antara nisbah ketinggian saluran kepada ketebalan lapisan sempadan (D/δν) di antara kajian ini dan penerbitan lepas turut dipersembahkan untuk mengukuhkan lagi kesahihan data kajian ini. Analisis menyeluruh terhadap pemahaman dinamik aliran seperti yang dilaporkan dalam kajian ini dijangka akan memberi manfaat kepada sistem yang beroperasi dalam keadaan aliran ayunan terutamanya sistem termoakustik.

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LIST OF ABBREVIATIONS AND SYMBOLS

AHX	-	Ambient Heat Exchanger
CFD	-	Computational Fluid Dynamics
CHX	-	Cold Heat Exchanger
DR	-	Drive ratio
PISO	-	Pressure-Implicit with Splitting Operators
PIV	-	Particle Image Velocimetry
SST	-	Shear-Stress Transport
TKE	-	Turbulent Kinetic Energy
UDF	-	User-Defined Function
UVP	-	Ultrasonic Velocity Profile
2D	-	Two-dimensional
T	-	Theoretical
E	-	Experiment
σ	-	Inertial number
D	-	Diameter of the pipe
D_h	-	Hydraulic diameter
d	-	Diameter of the pipe
ρ	-	Density of the fluid
ω	-	Angular frequency
ω'	-	Dimensionless frequency

μ	-	Dynamics viscosity
v	-	Kinematic viscosity
δ	-	Boundary layer thickness
δ_v	-	Boundary layer thickness
Re	-	Reynolds number
Re_δ	-	Reynolds number based on boundary layer thickness
U	-	Axial velocity amplitude
u_m	-	Velocity amplitude at the middle of the channel
A	-	Critical value of Reynolds number
Re_{crit}	-	Critical value of Reynolds number
λ	-	Stokes parameter
y_p	-	Distance from the wall to its position
R	-	Radius of the pipe
Λ	-	Stokes parameter
Re_ω	-	Kinetic Reynolds number
A_0	-	Amplitude of the oscillation
x_{max}	-	Maximum fluid displacement
ω_z	-	Vorticity
L_h	-	Characteristics length
u_{max}	-	Maximum velocity amplitude
Re_{max}	-	Maximum Reynolds number
Va	-	Valensi number
L_d	-	Entry length
L_a	-	Fluid displacement amplitude
u_1	-	Velocity

$h_{\kappa,1}$	-	Shape factor
ρ_m	-	Mean density
c_p	-	Specific heat capacity
P_1	-	Oscillating pressure
T_m	-	Mean temperature
x	-	Axial length
U_1	-	Volume flow rate
$\vec{v}$	-	Velocity vector
t	-	Time
τ	-	Stress tensor
p	-	Pressure
k	-	Thermal conductivity
T	-	Temperature
S_c	-	User-defined function
S_m	-	User-defined function
S_E	-	User-defined function
μ_t	-	Turbulent viscosity
γ	-	Intermittency
Γ	-	Effective diffusivity
δ_v	-	Viscous penetration depth
δ_k	-	Thermal penetration depth
λ	-	Wavelength
c	-	Speed of sound
f	-	Flow frequency
k	-	Wavenumber

π	-	Pi (3.14159)
L	-	Length of the resonator
H	-	Height of the resonator
x_s	-	Stack centre position
x_1	-	Inlet locations
x_2	-	Outlet locations
l	-	Length of the plate
d	-	Thickness of the plate
D	-	Channel's height
P_a	-	Acoustic pressure at the location of pressure antinode
P_m	-	Mean pressure
m_2'	-	Oscillating mass flux
θ	-	Phase
ℓ	-	Turbulent length scale
TI	-	Turbulent intensity
y^+	-	Location of the nearest node from the wall
m	-	Location at the middle of the stack
y	-	Distance from the wall
ϕ	-	Phase
Φ	-	Porosity
ξ	-	Displacement amplitude

LIST OF PUBLICATIONS

Mustaffa, S. H. A., Mohd Saat, F. A. Z. and Mat Tokit, E. 2018. Turbulent vortex shedding across internal structure in thermoacoustics oscillatory flow. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 46 (1), pp. 175-184.

Mustaffa, S. H. A., Mohd Saat, F. A. Z. and Mat Tokit, E. 2018. Numerical study of the entrance effects in an oscillatory flow of a standing-wave thermoacoustics. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 43 (1), pp. 149-157.

Mustaffa, S. H. A., Mohd Saat, F. A. Z. and Mat Tokit, E. 2017. Numerical investigation of turbulence in oscillatory flow found in thermoacoustics. *Proceedings of Mechanical Engineering Research Day*, pp. 1-2.

Mustaffa, S. H. A., Mohd Saat, F. A. Z. and Mat Tokit, E. 2016. Design of experimental test-rig to investigate turbulence in oscillatory flow used in thermoacoustics. *Postgraduate Symposium for Environmental Engineering Technology*.