ANALYSIS OF STACK GEOMETRY EFFECTS ON THERMOACOUSTIC WITH PARTICLE IMAGE VELOCIMETRY (PIV)

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This report writing is dedicated to my family, respectable supervisor and my supportive friends.

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ABSTRACT

Thermoacoustic refrigerator system generates cooling from acoustic energy. Acoustic waves interact with stack plates in the resonator tube of a thermoacoustic refrigerator to induce a temperature difference the significance of which depends on the solid-fluid interactions. In this study, the flow field at the end of the stack plates was investigated using Particle Image Velocimetry (PIV) method. Results were obtained from three stack configurations with different plate geometry. Effects of plate thickness and separation gap were determined by comparison of the velocity profile obtained from different configuration; separation gaps of 1mm and 3mm, and thickness of 1mm and 3mm. The ratio of separation gaps to viscous penetration depth was also determined to see the effect. For 1mm separation gaps, the ratio is about 6.27 and for 3mm it is 18.80. There are differences in the velocity within the separation gaps of stack plates. The velocity in the separation gap region for the 1mm is smaller compared to the 3mm separation gap due to the smaller ratio. A vortex is observed near the edge of the plate with thickness 3mm and there is no clear vortices seen near the stack for the 1mm thickness. The Reynolds number based on the plate thickness of 1mm and 3mm are 153.13 and 352.50 respectively. Wakes were observed behind the 3mm thickness stack plates but none behind the 1mm plate.

ABSTRAK

Sistem penyejukan termoakustik menghasilkan penyejukan dari tenaga akustik. Gelombang akustik berinteraksi dengan plat stack dalam tiub resonator pada sistem penyejukan termoakustik untuk menghasilkan perbezaan suhu yang bergantung kepada interaksi antara pepejal-cecair. Dalam tesis ini, medan aliran pada hujung plat stack dikaji menggunakan kaedah Particle Image Velocimetry (PIV). Keputusan diperoleh daripada tiga tatarajah stack dengan geometri plat yang berbeza. Kesan ketebalan plat dan jarak pemisah plat ditentukan dengan perbandingan profil kelajuan yang diperoleh daripada tatarajah berbeza; jarak pemisah 1mm dan 3mm, dan ketebalan 1mm dan 3mm. Nisbah jarak pemisah kepada kedalaman penembusan kelikatan juga dikira untuk melihat kesan. Untuk jarak pemisah 1mm, nilai nisbah adalah 6.27 dan untuk 3mm 18.80. Terdapat perbezaan dalam halaju di antara jarak pemisah plat stack. Halaju pada kawasan jarak pemisah untuk 1mm adalah lebih rendah berbanding dengan 3mm jarak pemisah disebabkan oleh nisbah yang rendah. Vorteks kelihatan pada hujung plat untuk ketebalan 3mm dan tiada vortex jelas kelihatan berdekatan stack 1mm ketebalan. Nombor Reynolds berdasarkan pada ketebalan plat untuk 1mm dan 3mm adalah masing-masing 153.13 dan 352.50. Keracak kelihatan pada belakang 3mm ketebalan plat stack tetapi tiada pada belakang 1mm plat.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Recently, considerations on the environmental aspects have become important issues in design and development of new systems. The refrigeration industry has been pointed as one of the main causes of ozone crisis, due to the production of chlorofluorocarbons (CFC) which also contributes to greenhouse effect. CFC is any organic compounds composed of carbon, fluorine and chlorine which were originally developed as refrigerants during the 1930s, and also found use as aerosol-spray propellants, solvents, and foam-blowing agents. They are well suited for these and other applications because they are nontoxic and non-flammable and can be readily converted from a liquid to a gas and vice versa.

CFCs were eventually discovered to pose a serious environmental threat. Studies indicated that CFCs, once released into atmosphere, accumulate in the stratosphere, where they contribute to the depletion of the ozone layer. Stratospheric ozone shields life on Earth from the harmful effects of the sun’s ultraviolet radiation, even relatively small decrease in the stratospheric ozone concentration can result in an increase incident of skin cancer in humans and genetic damage in many organisms. Thus, thermoacoustic refrigerator a system without CFC but uses inert gases instead is an alternative to this conventional refrigeration system that has caused much destruction to the ozone layer due to the production of CFCs.

Thermoacoustic is a combined phenomenon of acoustic and thermodynamics. Thermoacoustic effects are produced when pressure oscillations or acoustics generate a temperature gradient or vice versa. Thermal energy is moved through an elastic medium that is typically a compressible working fluid. Thermoacoustic effects will occur when temperature oscillations accompany the pressure oscillations and when there are spatial gradients in the temperature oscillation. Thermoacoustic engine can be classified into two basic kinds which are thermoacoustic prime mover and thermoacoustic refrigerator or thermoacoustic heat pump. A system that converts heat energy into acoustics is called a thermoacoustic prime mover while a system that converts acoustics into heat energy difference is called a thermoacoustic refrigerator.

In general, thermoacoustic engines can be divided into standing wave and travelling wave devices. In standing wave devices, the wave will remain at a constant position. The standing wave phenomena occurs when the reflecting wave traveling in the opposite direction with the same frequency meet up with the incoming wave. The interference between these two waves from opposite directions and at the same frequency will produce the stationary medium in devices. Whereas for traveling wave devices there are no reflecting wave occurrences and there is no stationary medium produced. This study will focus on the standing wave thermoacoustic refrigeration system.

Particle Image Velocimetry (PIV) is a particle tracer method of fluid visualization technique used to make flow patterns visible, in order to get qualitative or quantitative information on them. Typical PIV apparatus consists of a camera (normally a digital camera), a high power laser, an optical arrangement to convert the laser output light to a thin light sheet (normally using cylindrical lens and spherical lens), and a synchronizer to act as an external trigger to control the camera and laser while the seeding particles and the fluid is still under investigation.

PIV is an important experimental tool in fluid mechanics and aerodynamics. The basic principle involves photographic recording of the motion of microscopic particles that follow the fluid or gas flow. Image processing methods are then used to determine the particle motion, and hence the flow velocity, from the photographic recordings. Provided there are enough particles within the area of flow under investigation, the entire velocity field of the flow can be determined. The use of PIV technique is very attractive in modern aerodynamics. Examples of current applications are aircraft wake (measurement of the wake vortices of a lifting aircraft wing), helicopter aerodynamics (investigation of rotor aerodynamics with respect to noise emission of various noise sources such as blade or vortex interactions), and transonic flow over airfoils. Besides studies in aerodynamics, PIV is increasingly used in the investigation of liquid flows (vortex-free-surface interaction, thermal convection and Couette flow between concentric spheres).

A flow is visualized by seeding the fluid with small particles that follow the changes of the flow instantaneously. The light-sheet which is generated by a laser and a system of optical components is not continuous or permanent but pulsed to produce a stroboscopic effect, freezing the movement of the seeding particles. To detect the position of the illuminated seeding particles, a CCD-camera (CCD = Charge Coupled Device) is positioned at right angle to the light-sheet and the particle positions will appear as light specks on a dark background on each camera frame. The pulsing light-sheet and the camera are synchronized so that the particle positions of particular light pulse number 1 are registered on frame 1 of the camera and particle positions from pulse number 2 are on frame 2.

1.2 Literature Review

The stack is considered as the heart of a thermoacoustic system. Development and continuous improvement of it can better the overall performance of a thermoacoustic system. The heat transfer process crucial to thermoacoustic effects occurs in and near the stack region and current technology of the stack material and geometry has room for improvement based on the background studies completed. Various researchers have recommended various stack gaps using latest discovery of the best performance stack material.

It was Carter *et al.* (1962) who were responsible for introducing the stack in the thermoacoustic system. Starting from here, the stack was used to increase the thermoacoustic effects. Then Rott (1980) studied the circular and parallel stack. His study on the stack was put into the Rott's Function diagram, a diagram which is important in determining the stack boundary layers (Swift, 1988). Wheatley *et al.* (1986) then used tungsten as a stack with parallel plate geometry for his patented thermoacoustic device. In the same year, Hofler (1986) then used a camera film as a stack with spiral geometry for his PhD work. His geometry was considered simple to fabricate.

Arnott *et al.* (1991) then studied square, rectangular and triangular pores for the stack. The studies of these stacks were added into the Rott's function diagram in the year 1991. In 1992, STAR thermoacoustic refrigeration system was developed using Mylar with spiral roll as the stack. This was the big turning point in stack development, as many researchers after that used Mylar as stack because of its success. Keolian and Swift (1995) and Hayden and Swift (1997) mentioned the pin array stack. They proved that the pin-array is the best geometry for the stack. The main problem is the difficulties in fabricating the stack. Poese and Garret (1998) and Tijani (2001) then used parallel plates with Mylar as the stack.

Literature on acoustic flow field is generally extensive among the researchers. The flow fields were measured using various techniques and for thermoacoustic refrigerator investigation, optical method is more preferred due to its non-intrusive characteristic. Previous studies on thermoacoustic refrigerator show that the visualization flow field techniques that have been used are Holographic Interferometry, Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). Herman *et al.* (1998) used Holographic Interferomany for the visualization of the flow near the stack plate. Taylor (1976) was the first to measure the acoustic velocity in an acoustic resonator using LDA. And also Baillet *et al.* (2000) measure the acoustic power flow in a thermoacoustic resonator using this technique. These techniques only yield data for a single point in the measurement volume. Meanwhile, PIV is more preferred since it allows obtaining velocity data over a large area.

Besides, few researchers have ventured into PIV measurement technique to obtain the flow field around an acoustic stack of the thermoacoustic refrigerator.

Philippe Blance-Benon and his colleagues from the John Hopkins University, (2003) have visualized the oscillating flow field in a thermoacoustic stack using PIV measurement and compared the results with computational predictions obtained under similar condition. The author focused on stacks operating at low drive ratios, and presented results obtained with two stack configurations which are characterized by ratios of the plate thickness to the viscous penetration depths. For the thick-plate configuration, both experimental computational results revealed the presence of concentrated vortices near the edge of the plate. This is because the ratio of plate spacing to the viscous penetration depth is large and also the plate Reynolds number was high enough to permit vortex generation. As for the thin-plate configuration, the result did not show the formation of well-defined eddies that contrasted with the observation of the thick-plate configuration.

Mao *et al.* from the University of Manchester (2005) completed PIV measurement of coherent structures and turbulence created by an oscillating flow at the end of a thermoacoustic stack. The author's objective was to identify the flow morphology and turbulence characteristics in the vicinity of the parallel-plate thermoacoustic stack. Two stack models were tested; thin and thick stack with area of the stack kept constant. The results showed that there were significant differences between the low drive ratio (D_r<1%) for thick stack and high drive ratio (D_r>1%) for thin stack. Drive ratio is the ratio between peak pressure (P_A) amplitude to mean pressure (P_m) in the resonator, $D_r = \frac{P_A}{P_m}$. The flow on the thick stack is dominated by laminar-like features. The vortices formed at the edges of the plates in the ejection phase and finally the vortices that formed were sucked back between the plates when the velocity changed its direction. And for the thin stack the high vorticity regions were much more elongated. During the ejection phase coherent vortex structures were being shed from the edges of the plates.

Berson and his colleagues (2008) also used PIV technique to address the characterization of the flow inside a thermoacoustics refrigerator and the measurement technique was validated by comparing the velocity fields obtained in the resonator without stack to a simple plane wave model. The oscillating boundary layers between two plates of the stack were investigated and the generation of vortices at the edges of the stack plate was precisely described. Effect of the acoustic pressure level on the vortices was also investigated by the author. Although validated, results had some limitations on the linear model at higher acoustic pressure level when nonlinearities appeared. The acoustic velocity fields behind the stack plate were characterized and showed vortices appearing during half periods of the acoustic cycle when the fluid flowed out of the stack. For the effect of acoustic pressure level, counter-rotating vortices were generated at the edges of the plates at low pressure level and they were symmetrical and remain attached to the plates. With increasing acoustic pressure level, structures detached and developed a symmetrical street of vortices.

A recent study by Shi *et al.* (2009) investigated vortex shedding processes occurring at the end of the stack of parallel plates due to an oscillating flow induced by an acoustic standing wave. PIV and also Hot-Wire Anemometry (HWA) were used. PIV were used to quantify the vortex shedding processes within an acoustic cycle phase-by-phase, in particular during the ejection of the fluid out of the stack. Meanwhile, HWA was applied to detect the velocity fluctuations near the end of the stack. Combination of these two measurement techniques provided a detailed analysis of the vortex shedding phenomena. Impact of the plate thickness and the Reynolds number on the vortex shedding pattern also had been discussed by the author in this study. Table 1.1 list out past studies completed with PIV method.

Table 1.1: Summary of literature review on PIV method.

Author	Resonator	Stack	Working Fluid	Remark
Blance-Benon, P. *et al.* (2003)	86cm long	Parallel plate Glass plate Thickness: 0.15mm,1mm Separation gap: 1mm, 2mm	Air	thick-plate configuration revealed the presence of concentrated vortices near the edge of the plate, thin-plate configuration result does not show the formation of well-defined eddies
Mao, X. *et al.* (2005)	7.4m long, $136x136mm^2$	Parallel plate 200mm long, 136mm wide. Thickness: 1mm, 5mm Separation gap: 5mm, 10mm	Air, atmospheric pressure	The flow on the thick stack is dominated by laminar-like features - the vortices formed at the edges of the plates, for the thin stack the high vorticity regions are much more elongated
Berson, A. *et al.* (2008)	Plexiglass 86cm long, $80x80mm^2$	Parallel plate Glass 25mm long Thickness: 1mm Separation gap: 1mm	Air, atmospheric pressure	vortices appearing during half periods of the acoustic cycle when the fluid flowed out of the stack, counter-rotating vortices were generated at the edges of the plates at low pressure level, symmetrical street of vortices develop with increasing acoustic pressure level
Shi, L. *et al.* (2009)	Metal Tube 7.4m long, $134x134mm^2$	Parallel plate 200mm long, 132mm wide. Thickness: 0.5-5mm Separation gap: 1.2mm-10.8mm	Air, atmospheric pressure, room temperature	At thin stack a pair of attached vortex structures at the end of the plate form and elongated as the velocity gradually increases, when thickness increase the attached symmetrical vortex structures are no longer elongated but begin to break up early and into discrete vortices

1.3 Problem Statement

In the high-intensity acoustic field, the flow structures at the end of the stack are very complex due to discontinuities of the cross section and the oscillatory nature of the flow. The energy transfer taking place within the thermoacoustic stack will be affected by entrance/exit effects, vortex shedding and generation of the turbulence over different parts of the acoustic cycle (Mao *et al.*, 2008). In order to optimize the stack which form the heart of the cooler in a thermoacoustic refrigerator, the coefficient of stack performance, defined as the ratio of heat pumped by the stack to the acoustic power used by stack, has to be maximized (Tijani, 2001).

Thus, to improve thermoacoustic refrigeration system, a better understanding on the flow field around the component of stack is important. This study involves an experimental analysis of a flow around the thermoacoustic stack and also the effects of the stack geometry on this flow field. The flow around the stack is visualized experimentally using PIV.

1.4 Research Objectives

Objective of this research is to investigate the effect of the stack geometry (thickness and separation gaps) on thermoacoustic effects using Particle Image Velocimetry (PIV).

1.5 Scope of the Study

The scopes of this research are to:

1. Design appropriate thermoacoustic resonator geometry and associated stack for the resonator tube for a PIV experimental set-up.
2. Fabricate stack geometry of different thickness and separation gaps.
3. Complete experiments with PIV to investigate the effects of the stack geometry and space beyond the stack on velocity profiles.

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BR	-	Blockage ratio
C	-	Sound speed
CCD	-	Charge coupled device
CFC	-	Chlorofluorocarbons
c_p	-	Isobaric specific heat of the gas
D_r	-	Drive ratio
f	-	Frequency
HWA	-	Hot-wire anemometry
h @ $2y_o$	-	Separation gap
K	-	Thermal conductivity
L	-	Length
LDA	-	Laser doppler anemometry
UTM	-	Universiti Teknologi Malaysia
PhD	-	Doctor of philosophy
PIV	-	Particle image velocimetry
Pr	-	Prandtl number
P_A	-	Peak pressure
P_m	-	Mean pressure
p_A	-	Pressure distribution
Re_d	-	Reynolds number
SHM	-	Simple harmonic motion
t @ $2l$	-	Thickness
u_A	-	Velocity distribution
v	-	Velocity
w	-	Width
x	-	Distance
x_c	-	Stack center position

x_{td}	-	Tidal displacement
λ	-	Wavelength
λ_{ac}	-	Wavelength of the standing wave
Δx	-	Stack of plates of length
ΔT	-	Temperature difference
ω	-	Angular frequency
δ_{α}	-	Thermal penetration depth
δ_{v}	-	Viscous penetration depth
ρ_{m}	-	Density
μ	-	Dynamic viscosity
β	-	Thermal expansion coefficient