NUMERICAL SIMULATION OF STANDING WAVE IN AN ACOUSTIC CHAMBER

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To my beloved family for their understanding, supports, and most of all, love.

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ABSTRACT

Numerical simulation of two-dimensional unsteady compressible Navier-Stokes equations which consists of mass, momentum, and energy conservation equations, and the equation of state is implemented using a commercial CFD code in a standing wave acoustic chamber. The stack is modelled as a two-dimensional thickness. In this study, heat flux across stack surface placed axially in a resonator was investigated. Heat flux distribution was found to peak at the plate edges. It was observed that energy flow from a "source" at the left end to a series of "sink" at the right end of the plate. At near the middle of the stack, there is no appreciable net energy exchange with the working fluid, and energy could be found to almost being transported axially along the direction from the source to the sink.

ABSTRAK

Simulasi berangka dua dimensi aliran boleh mampat transien ke atas persamaan Navier-Stokes yang merangkumi persamaan pengabadian jisim, momentum, dan tenaga serta persamaan keadaan telah dilakukan. Simulasi dilakukan dengan kod program komersil untuk aliran di dalam kebuk gelumbang akustik dengan plat tindan dua dimensi. Fluks haba yang merentas permukaan tindan menunjukkan kehadiran puncak di kiri dan kanan plat tindan. Tenaga bergerak dari "sumber" pada hujung kiri ke arah kanan plat tindan. Tiada petukaran tenaga haba yang ketara berlaku di antara plat dan bendalir kerja pada bahagian tengah

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Nomenclature

a – Speed of sound in working fluid

C_p – Specific heat capacity at constant pressure

CFD – Computational Fluid Dynamics

f – Operating frequency

k_0 – Thermal conductivity

k – Wave number

L – Length of resonator

M – Mach number

n – Mesh intervals

P – Pressure

R – Gas constant

Re – Reynolds number

S – Stack domain

Sym - Symmetry

T – Temperature

t – Time

u – Velocity in x-direction

v – Velocity in y-direction

y_0 – Half-spacing between plate centreline

y_s – Plate half-thickness

Greek Symbols

ω - Angular velocity

β - Coefficient of thermal expansion

ρ – Density

μ - Dynamic viscosity

ν - Kinematic viscosity

σ - Prandtl number

γ - Specific heat ratio

$\overline{\overline{\tau}}$ - Stress tensor

δ - Thermal penetration depth

Φ - Viscous dissipation

λ – Wave length

Subscripts

1 – Before stack

2 – After stack

a - acoustic

A - Amplitude

al - Aluminium

k – Working fluid

m – Mean

my - Mylar

s – Stack

x – x-direction

y – y-direction

δ – Critical

CHAPTER 1

INTRODUCTION

1.1 Overview of Acoustics

Acoustic waves can be generated by various sources. Usually acoustic waves are generated by mechanical vibrations, such as wall vibration or shaking of a chamber. They can also be created by some thermal actions, such as rapid heating/cooling, combustion, special arrangement of heat source and sink, and so on. In this work, the standing waves driven by wall vibrations in an acoustic chamber shall be focussed on.

Thermoacoustics is a field of study that uses high-amplitude sound waves in a pressurized fluid to pump heat from one place to another. The study includes devices purpose-built to exploit the phenomenal interaction between heat and sound. Thermoacoustic devices are typically characterized as either ‘standing-wave’ or ‘travelling-wave’ configurations, where the thermodynamic processes occur in a closed vessel.

Acoustic-fluid interactions are found in many natural phenomena and industrial applications are finding uses in thermoacoustic engines, refrigerators, cryogenics and electricity generation. An example of a standing-wave thermoacoustic refrigerator schematic, is shown in Figure 1.1.1 (Reid et al, 2000), and in a commercial application in Figure 1.1.2 (Triton: Shipboard Thermoacoustic Cooler, 2005).

The design of this air-conditioner is similar to a conventional one, only the vapour compression system has been replaced with a thermoacoustic system. The main components are shown in the middle tube in Figure 1.1.1 and comprises of a closed cylinder, an acoustic driver, a stack, and two heat-exchanger systems. The length of the closed cylinder is typically a half or quarter wavelength of the driving frequency. The vessel becomes resonant after the application of the acoustic driver, and the pressure and particle velocity distributions are shown on the right hand side of Figure 1.1.1. The upper tube system in Figure 1.1.1 is used to dissipate heat from the thermoacoustic system to ambient air. The lower tube system is used to transfer heat from the indoor air to produce a cold air stream. The heat-exchangers are used to improve the transfer of heat between the sub-systems. The example of a standing-wave thermoacoustic refrigerator is shown in Figure 1.1.2, was developed at Penn State University (Triton, 2005). The device provided 10kW of cooling power, and used a double Helmholtz resonator design to increase the cooling capacity. The product has a cooling output that is suitable for a small business or large home.

Thermoacoustic systems are classified into two different classes known as 'heat-engines' (also known as 'prime movers') and 'heat-pumps'. In principle, heat-engines remove heat energy from a hot reservoir, convert some of the heat energy into acoustic energy and dump the unused heat to a cool reservoir. On the other hand, heat-pumps use acoustic energy to pump heat from one temperature reservoir to another resulting in a temperature gradient between the two reservoirs.(Zoontjens, 2008).

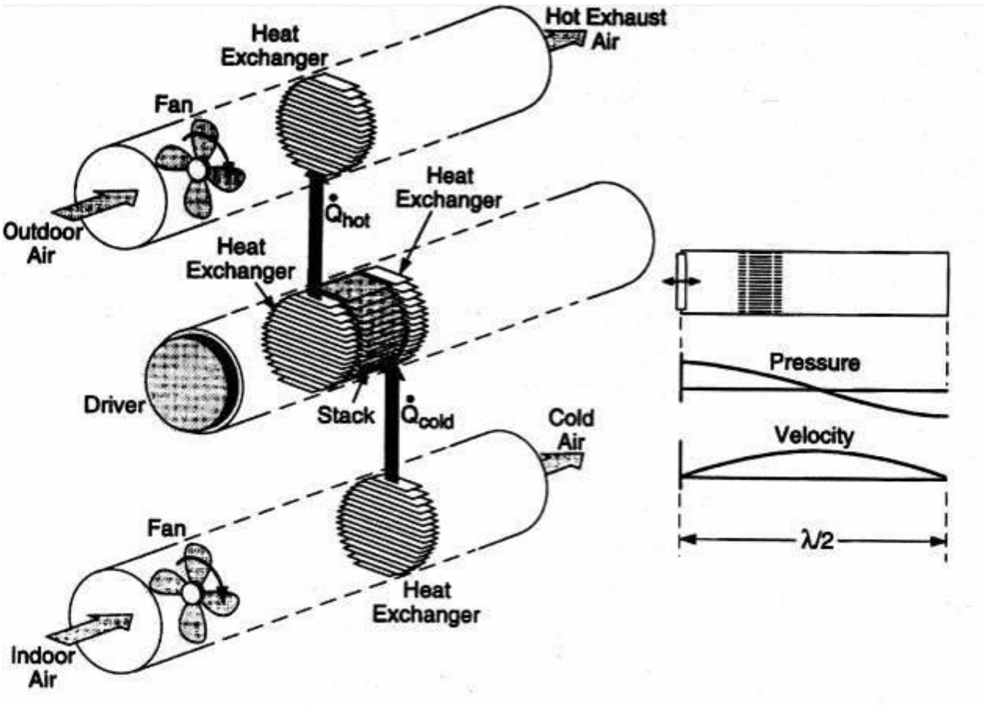

Figure 1.1.1: A typical standing-wave thermoacoustic refrigerator schematic (Reid et al, 2000).

Figure 1.1.2: Standing-wave thermoacoustic refrigerator (Triton: Shipboard Thermoacoustic Cooler, 2005).

Since the thermodynamic cycle by which thermoacoustic systems operates is ideally reversible, refrigerators are typically driven by either a mechanical fluid displacement system (such as a loudspeaker or a piston) or a heat-engine. A loudspeaker or an electro-dynamic shakers convert electrical power into acoustic power, are relatively easy to implement.

Thermoacoustic devices are unique amongst refrigeration systems in their use of helium gas. According to Zoontjens (2008), the environmental benefits that exist using helium in thermoacoustics over conventional refrigeration technologies include:

- Zero global warming potential from direct emissions;
- Zero ozone depletion potential from direct emissions;
- The working gas is non-toxic and non-combustible; and
- The working gas does not necessarily need to be recaptured if replaced.

1.2 Literature Review

In this section, the relevant literature of acoustics-fluid interactions in a standing wave is reviewed. Specific aspect of thermoacoustic phenomena that are directly connected with the content of this work shall be focused on.

Cao et al (1996), integrated numerically the compressible viscous fluid equation to investigate the energy flux inside a thermoacoustic couple. Oscillatory boundary at inlet and no-slip boundary condition on walls was applied to the thermoacoustic resonator to obtain a standing wave in the simulation chamber. SOLA-ICE method was use to discretize the governing equations (Navier-Stokes).

The dissertation of Mohd. Ghazali (2001) reported the numerical simulation of acoustic waves in a closed two dimensional rectangular chamber. Finite difference spatial discrete and semi-implicit time marching procedure was used to numerically solve the Navier-Stokes equations. Result showed that the flow pattern was more complicated than the expected standing wave with other features like beating, crosswaves, streaming, oscillatory boundary layers and vortex motion. The boundary conditions were no-slip, no-penetration, and zero heat flux.

Ishikawa and Mee (2002), and Marx and Blanc-Benson (2004) adopted a computational domain similar to that of Cao et al. (1996) where the plate thickness was assumed to be zero thickness. Ishikawa and Mee (2002) simulated the flow field and the energy transport near thermoacoustic couples using a 2D full Navier-Stoke solver. They also investigated the effects of plate spacing and the amplitude of the standing wave, and their results were examined in the form of energy vectors, particle paths, and overall entropy generation rates. Ishikawa and Mee (2002) observed that energy dissipation near plate increased quadratically as the plate spacing was reduced.

Wan et al (2003) studied acoustic streaming for enhancing heat transfer in a channel composed of two parallel beams. A rectangular heat source was attached to the upper beam. The lower beam, kept at a constant and uniform temperature, vibrates and scattered standing acoustic waves into the gap, which induced acoustic streaming in the gap due to non-zero mean of the acoustic field. Perturbation method was utilized to decompose the compressible Navier-Stokes equations into the acoustic first order equations and the second order streaming. The governing equations were descritized by finite-difference method on a uniform mesh and solved numerically. Non-reflective boundary conditions were imposed at the open ends. No-slip boundary conditions were imposed on both fixed and vibrating solid surfaces.

Aktas et al. (2004), investigated the generation and propagation of thermoacoustic waves in water by numerically solving a fully compressible form of Navier–Stokes equations, taking into consideration all nonlinear and diffusion effects. An explicit finite difference approach was used to solve the discretized form of the governing equations. The convective terms were discretized using a flux-corrected transport (FCT) algorithm while the diffusion terms were discretized by a central-difference scheme. Very small time steps were required to capture the generation and propagation of thermoacoustic waves by rapid heating. The predicted shape and strength of the thermoacoustic waves in water were quite different than those computed for gases. Important differences were also identified for the generation of thermoacoustic waves in water and in gases. These were due to large density and compressibility differences between water and gases. The pressure changes for impulse and gradual temperature increase cases were much higher due to the low compressibility of water. The water media confined in a square enclosure was initially considered to be quiescent and at atmospheric pressure with an initial temperature T_i. The boundary conditions for the higher order FCT-based solutions of the Navier–Stokes equations require a rigorous formulation. No-slip boundary conditions were used for velocity on all walls. Adiabatic temperature boundary conditions were used for the bottom and top walls. The right wall temperature was maintained at the initial temperature of the water. The left wall temperature was varied either impulsively.

In Aktas (2004) dissertation, the behaviour of acoustic waves induced by thermal and mechanical effects and the interaction of these waves with flow fields and rigid walls were investigated. Thermoacoustic convection and acoustic streaming were analyzed using computational and experimental techniques. A standing wave field in a two-dimensional enclosure was created by the vibration of one side wall of the enclosure. The computations were carried out using a Fortran code to perform one dimensional flux-corrected transport algorithm known as LCPFCT (Laboratory for Computational Physics, Flux-Corrected Transport) algorithm .The interaction of this wave field with the solid boundaries led to the production of Schlichting (inner) and Rayleigh (outer) type acoustic streaming flow patterns in the enclosure. The effect of the enclosure height and the amount of maximum wall displacement for vibratory motion were studied primarily. These parameters played significant role in the characteristics of the resulting flow structures. It was found that the streaming patterns varied strongly with a change of the standing acoustic wave form from ‘harmonic wave profile’ to ‘sharp shock wave’ type profile. Boundary conditions were no-slip wall and heat conducting or thermally insulated wall conditions.

Marx and Blanc-Benson (2004), calculated numerically the temperature difference between the extremities of the plate. They found that one extremity of the plate heated up while the other end cooled down when placed in a thermoacoustic resonator due to the systems thermoacoustic effect. Some discrepancies were found at low mach acoustic number which they claimed could not be attributed to non-linear effect, rather they existed because of thermal effects.

Hossain et al (2005) developed a linear theory to estimate the resonant frequency and the standing wave mode in closed ducts with variable cross sectional area. The finite amplitude standing wave in closed ducts with area contraction was numerically studied. The effect of area contraction ratio and the gas properties on nonlinear standing wave was investigated. One-dimensional numerical simulation was conducted using fundamental fluid dynamics equations taking the effects of viscosity and frictions into consideration. Finite difference MacCormack scheme was used by preserving the computational accuracy within second-order in time and fourth-order in space, respectively. Their study showed that the amplitude of the standing wave and nonlinear phenomena largely depends on the shape of the duct; changes in duct geometry can have a significant impact on overall performance of acoustic compressors.

Vanhille and Campos-Pozuelo (2005) studied the behaviour of high-power ultrasonic standing waves in axisymmetric resonators experimentally and numerically. A rigid walled cavity excited by a narrow band transducer of finite dimensions was considered. The quality factor of the resonator, the displacement amplitude and distribution of the excitation, and the evolution of pressure amplitude and waveform with excitation were experimentally quantified. A full nonlinear axisymmetric wave equation written in Lagrangian coordinates was proposed. A time domain numerical model, based on a finite difference algorithm, was developed to solve it.

The numerical study of Lycklama à Nijeholt et al. (2005) considered the full length of an entire travelling wave thermoacoustic heat-engine using a two-dimensional domain and employed solution of unsteady Navier-Stokes formulations. Lycklama à Nijeholt et al. used an axisymmetric computational domain which extended the entire axial length of an enclosed double Helmholtz resonator. A commercial CFD code was used to solve the governing equation. The results of the computations showed the onset of self-oscillations accompanied by an increase of the dynamic pressure. Amplification of the acoustic power through the regenerator was also shown. Nonlinear phenomena like streaming mass flows and vortex formation were also visualized.

Aktas et al. (2005) investigated numerically thermal convection in a differentially heated shallow enclosure due to acoustic excitations induced by the vibration of a vertical side wall. The fully compressible form of the Navier-Stokes equations was considered and an explicit time marching algorithm was used to track the acoustic waves. No-slip boundary conditions were used for all solid walls. Numerical solutions were obtained by employing a highly accurate flux corrected transport algorithm. The frequency of the wall vibration was chosen such that an acoustic standing wave formed in the enclosure. The interaction of the acoustic standing waves and the fluid properties triggered steady secondary streaming flows in the enclosure. Simulations were also carried out for “off-design” vibration frequency where no standing waves were formed. The effects of steady second order acoustic streaming structures were found to be more significant than the main oscillatory flow field on the heat transfer rates. The model developed could be used for the analysis of flow and temperature fields driven by acoustic transducers and in the design of high performance resonators for acoustic compressors.

Zoontjens et al. (2009) modeled a system of thermoacoustic couples of non-zero thickness which was implemented by using a commercial CFD code. Zoontjens et al. (2009), and Tasnim and Fraser (2010) imposed an oscillatory boundary condition at the inlet of their simulation domain that is similar to that of Ishikawa and Mee (2002) work. Zoontjens et al. (2009) investigated the effect of drive-ratio and plate thickness upon the time-average heat transfer through the stack plate. Results obtained showed that plate thickness strongly controlled the generation of vortices outside the stack region, perturbing the flow structure and heat flux distribution at the plate extremes.

Tasnim and Fraser (2010), numerically simulated the unsteady compressible Navier-Stokes, continuity, energy equations, and the equation of state thereby investigating the hydro- and thermodynamic processes near and within two-dimensional stack plates using commercial code, STAR-CD. They observed the vortical mean flow at the extremities of the stack plate which is due to the abrupt change of a slip condition to a no-slip velocity boundary condition. The stack temperature was governed by energy equation thereby treating the entire domain as a conjugate heat transfer problem.

Zink et al. (2010) presented an extension of a simulation of a whole thermoacoustic engine that also included a refrigeration stack. They demonstrated the cooling of working gas in the stack through interaction of thermally generated sound. A decrease in temperature below ambient was proven.

1.3 Problem Statement

A two-dimensional rectangular enclosure is considered (figures 1.3.1 and 1.3.2). The top and bottom boundaries are fixed walls. The left wall of the enclosure is modelled as a rigid boundary which vibrated harmonically and represented the motion of a loudspeaker. The vibrating boundary is the acoustic source in this geometry. The right wall of the enclosure is fixed. Initially the gas in the enclosure is quiescent and kept at the constant mean temperature and pressure. The frequency of the wall vibration and the length of the enclosure are chosen such that an acoustic standing wave is formed in the enclosure. The enclosed stack plate material and the surrounding walls shall be selected to have good thermal capacity but poor thermal conductivity (Zoontjens , 2009).

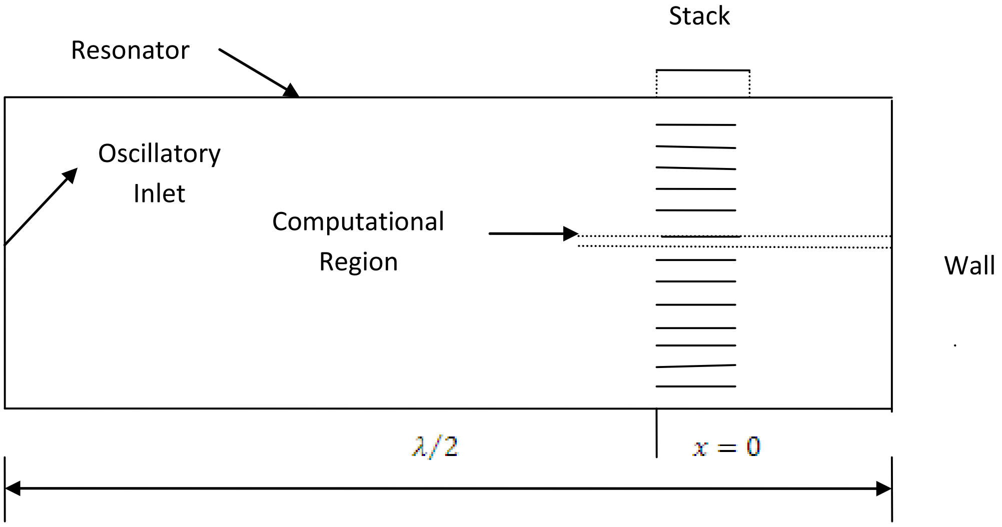

Figure 1.3.1: Schematic illustration of two-dimensional rectangular acoustic chamber (Zoontjens et al., 2009)

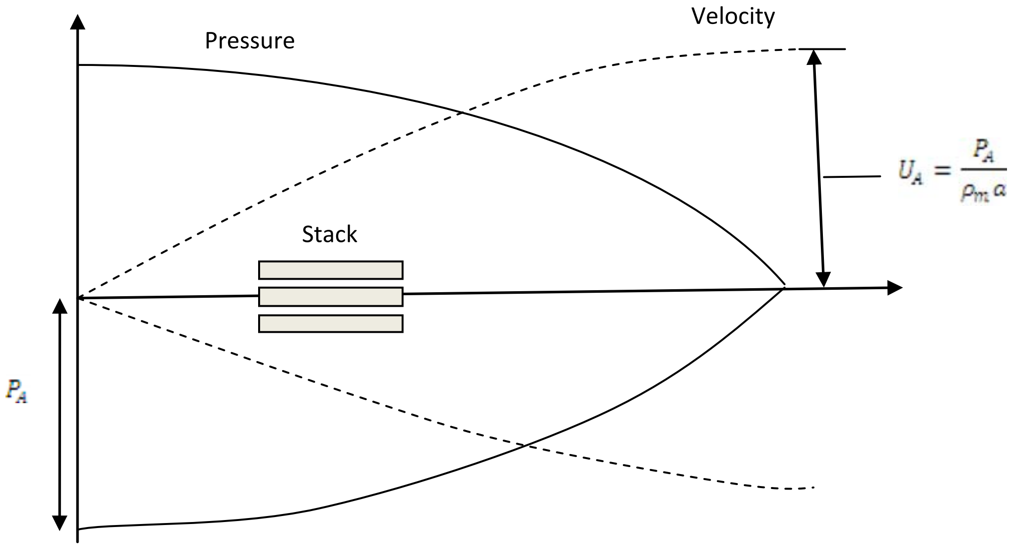

Figure 1.3.2: Stack position in the acoustic chamber.

1.4 Objective

The objective of this work is to numerically simulate a standing wave in an acoustic chamber using a computational fluid dynamics software package, FLUENT 6.2® (Fluent Inc., 2005) with the aim of investigating the thermal and flow behaviour of the working fluid.

1.5 Scope

In this study, standing acoustic waves in a rectangular closed chamber has been simulated numerically using FLUENT. The thermal and flow behaviour of the working fluid along the stack surface has been investigated. The results obtained numerically were compared with results from previous studies.