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The Prospective of Particle Image Velocimetry (PIV) Measurement Velocity Profile in Thermoacoustic System

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Abstract: Precise measurement of fluid velocities is essential in several applications, including thermoacoustic refrigeration systems. A thermoacoustic refrigeration system uses a high-amplitude acoustic standing wave to generate a cooling effect. Understanding the fluid flow characteristic between the refrigerant and a stack is important to improve the heat transfer process and minimise thermal and viscous losses. This paper reviews the various methods employed by previous researchers in analysing the velocity profiles in the thermoacoustic refrigeration system and the prospective implementation of Particle Image Velocimetry (PIV). PIV is a non-invasive technique that estimates velocity at several points of the measuring region. This review looked at the method employed to analyse the velocity profile, error analysis, and the effectiveness of another measurement method compared to the PIV measurement. The discussions include related parameters that past researchers have considered.

Keywords: Thermoacoustic, Velocity profile, Particle image velocimetry

Introduction

The development of thermoacoustic technology is motivated by the prospect that this technology can replace and reduce reliance on the current vapour compression technology. One of the significant contributions to the current environmental and energy crisis the world faces is cooling technology. Cooling technology generates hazardous gases that are released into our environment at a high energy cost. Thermoacoustic technology is an emerging technology that aims to convert low and medium temperature waste or solar heat into cooling or electricity, domestically and in the industrial. The thermoacoustic refrigerator is an innovative alternative for clean cooling. To summarise, the benefits of the thermoacoustic system include environmental friendliness, potentially high reliability due to the simple structure and the minimum number of moving parts, and reasonable efficiency(Nazmi et al., 2021).

Efficiency is always the primary concern related to the thermoacoustic system (Zolpakar et al., 2016). Under the same design and operating conditions, the thermoacoustic refrigerator's efficiency is only half of the conventional vapour-compression refrigerator (Tartibu, 2016). The efficiency of the thermoacoustic refrigerator is affected due to the acoustic and streaming losses in the thermoacoustic mechanism. It is identified that thermal and viscous losses are considered significant losses contributing to the thermoacoustic refrigerator's reduction in performance.

Thermoacoustic refrigerators work based on a thermal interaction between an oscillatory compressible flow and the solid structures, which are the stack and heat exchanger. The function of the stack is to produce a refrigeration effect by inducing acoustic excitation. These heat transfer processes are based on the 'thermoacoustic effect' whereby appropriately phased pressure, and velocity oscillations enable the compressible fluid to undergo a thermodynamic cycle in the vicinity of the stack. Figure 1 shows the heat flux streams between the device and the surroundings and the internal heat transfer streams on the interfaces between the stack and heat exchangers. One of the main obstacles in designing a thermoacoustic system is the lack of reliable heat transfer correlations for the oscillatory flow conditions (Shi et al., 2010b). Most of the time, it is assumed that the length of the heat exchangers should simply be equal to the displacement amplitude of the fluid particle, while the heat transfer rates are predicted using correlation for steady flow conditions. This shows the need for experimental investigations on heat transfer rates in the oscillatory flows to developing relevant heat transfer correlations for the thermoacoustic device environment.

As discussed in the above paragraph, a thermoacoustic system's heat transfer depends on the resonator tube's velocity and pressure profile. Therefore, this review is driven by the need for a better understanding of the methods employed by previous researchers in determining heat transfer rates, precisely the method of velocity measurement for the thermoacoustic system. This is crucial because the characteristics of the velocity of oscillatory flow are one of the determinants of achieving higher thermodynamic efficiencies and improving the performance of the overall thermoacoustic system.

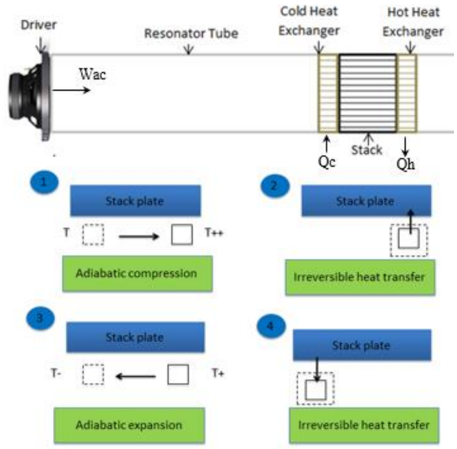

Figure 1. General schematic of the overall heat fluxes in a standing wave thermoacoustic refrigeration

General Review on Velocity Profile Measurement

There are several possible ways of obtaining reliable heat transfer information (velocity profile, temperature distribution, and pressure) to perform detailed quantitative measurements for a thermoacoustic system. This brief review paper divides the methods for measuring velocity profiles into two categories: simulation-based and experimental-based. The simulation-based methods involve Computational Fluid Dynamic (CFD) and Design Environment for Low Amplitude Thermoacoustic Energy Conversion (DeltaEC) ways to determine the velocity profiles. Meanwhile, for experimental-based, three methods were applied by the previous researchers, which are Hot-Wire Anemometry (HWA), Laser Doppler Anemometry (LDA), and Particle Image Velocimetry (PIV). Based on the limited number of past research works done in investigating the velocity profile of thermoacoustic systems, 65% of the researchers prefer to conduct research using simulation-based methods, especially the CFD method, compared to experiment-based, which only encompass 35%. This may be due to the high cost of setting up the experiment rig that involves specific components, especially for PIV and LDA setup. The details for every measurement are discussed in the following section.

Simulation Work in Measuring Velocity Profile

In the thermoacoustic system, DeltaEC (Design Environment for Low Amplitude Thermoacoustic Energy Conversion) is the only software built specifically for the use of the system and was developed by Ward et al. (Ward et al., 2017). DeltaEC has been extensively used either in the preliminary design of a thermoacoustic system or as data validation. Zoontjens et al. (Zoontjens et al., 2006) used DeltaEC as an initial design process in designing their thermoacoustic refrigerator. This study also applied Ansys, a CFD software used to compare results from DeltaEC, experimental work was performed for verification. Based on the experiment results, even though DeltaEC is a one-dimensional analysis, the software provided adequate accuracy to enable the design of devices. Other researchers, like Tijani et al. (Tijani et al., 2002), Tasnim et al. (Tasnim et al., 2012), and Hariharan et al. (Hariharan et al., 2012), used DeltaEC as a tool to validate their experiment results. Even though DeltaEC shows excellent benefits in terms of high speed of calculation and good agreement with experimental work, it also suffers from significant drawbacks, such as the need for relatively good estimation for DeltaEC to converge. In addition, this software can only solve 1D problems with minimum ability to detect nonlinear flows, such as turbulence and streaming effects (Tomas & Tomas, 2018). Thus, for researchers who want to investigate the effect of oscillatory flow on the thermoacoustic system, it is better to consider other software, such as CFD and OpenFOAM.

The most widely used method in measuring velocity profiles for thermoacoustic systems is the Computational Fluid Dynamic (CFD) method. Most researchers prefer the CFD method due to the ability of the software to examine the physical properties of fluid flow, such as velocity, pressure, temperature, density, and viscosity. The pioneer researcher that applied CFD in the whole thermoacoustic system is Zoontjens (Zoontjens et al., 2008), who also investigated fluid behaviour during the thermoacoustic cycle with a single plate stack. Other researchers who used CFD in their works are listed in Table 1.

Table 1. List of studies using CFD

No	Author, Year	Methodology	Part of simulation	Parameter measured
1.	Zink et al., (Zink et al., 2010)	CFD	TAR/TAE	Velocity, temperature, and heat flux
2.	Zoontjens et al. (Zoontjens et al., 2008)	CFD	Resonator with single plate stack	Fluid behaviour in thermoacoustic cycle
3.	Hanschk et al. (Hantschk, C.C Vortmeyer, 1999)	CFD	Rijke tube	Pressure and velocity amplitude
4.	Entezam et al. (Entezam & Moorhem, 1997)	CFD	Rijke tube	Relationship of velocity and pressure to the heat transfer process
5.	Rahpeina & Ebrahimi (Rahpeima & Ebrahimi, 2019)	2D COSMOL	TAR	Cooling temperature, COP
6.	Mohd Saat et al.(Mohd Saat et al., 2019)	2D CFD	TAR	Velocity distribution
7.	Allafi et al.(Almukhtar Allafi et al., 2021)	ANSYS FLUENT CFD	TAR	Velocity profile
8.	Allafi and Mohd Saat, (Almukhtar et al., 2020)	ANSYS FLUENT CFD	TAR	Velocity profile in entrance and exit at the stack plate
9.	Skaria et al. (Skaria et al., 2015)	CFD and DeltaEC	SWTAPM, TWTAPM, SWTAR	Pressure, temperature, and contour,
10.	Xiao et al. (Xiao et al., 2020)	CFD	Thermoacoustic Heat Dissipation System	Temperature gradient, fluid oscillating amplitude
11.	Namdar et al. (Namdar et al., 2015)	OpenFOAM CFD	Single plate stack, heat exchanger, resonator	Temperature gradient
12.	Kuzuu & Hasegawa (Kuzuu & Hasegawa, 2017)	CFD	Thermoacoustic engine	Temperature gradient
13.	Tisovsky and Vit, (Tomas & Tomas, 2018)	OpenFOAM	TAR/TAE	Acoustic pressure and velocity
14.	Narasimmanaidu et al. (Narasimmanaidu et al., 2021)	CFD	Porous Structure of Stack	Flow behavior

A study conducted by Mohd Saat et al. (Mohd Saat et al., 2019) found that the velocity prediction starts to deviate from the linear theory with a drive ratio of 1% when using the CFD method. In this paper, the researchers also observed that the length of the plate greatly influences the velocity change within the channel even though the porosity of the structure and the flow condition are the same. This finding opposes the theoretical equation whereby it is stated that the length of the stack does not affect the velocity calculation. Hence, this study suggested that the length of the stack influencing the velocity profile within the channel should be considered in the theoretical equation. The researchers also observed the formation of a vortex-shedding phenomenon at the end of the stack plate. As the drive ratio increases, the returning vortex on the velocity within the channel becomes more significant; thus, the turbulent effect must be seriously considered in the thermoacoustic analysis. This result is supported by Allafi et al. (Almukhtar Allafi et al., 2021) which formed two vortex layers near the surface of the solid structure as a result of the CFD method, as shown in Figure 2. The layers are named the main and the secondary vortex layers, and they move with the cyclic flow and affect the shape of the velocity profile within the channel. The latest finding follows this by Allafi et al. (Almukhtar et al., 2020), which presents the entrance and exit effects of oscillatory flow within a parallel-plate structure inside the resonator. Allafi and his team concluded that oscillatory flow across a parallel-plate structure is commonly found in the thermoacoustic system, and the effect of developing flow to the thermoacoustic performance should be seriously considered in the design.

The prior study by Kuzuu and Hasegawa (Kuzuu & Hasegawa, 2017) investigated the acoustic characteristics and temperature field of the oscillatory flow around the thermoacoustic device using the CFD method. The study found that the vortex generation near the driver causes high energy dissipation, but it is still acceptable according to the linear theory. Meanwhile, the asymmetrical temperature oscillation was measured within the heat exchangers for the temperature distribution. The authors argued that this behaviour could not be predicted using the linear theory because the non-uniform temperature gradient in the engine unit is transferred stream-wise by convection. Meanwhile, Namdar et al. (Namdar et al., 2015) studied the effect of the pressure nodes on the temperature of the heat exchanger in the thermoacoustic system using CFD software. The optimum location of the heat exchanger was determined by plotting a pressure and velocity distribution in the resonator. This result shows the importance of simulation work and how it helps in visualising the thermoacoustic effect and understanding the parameters that need to be investigated to improve the performance of the thermoacoustic system.

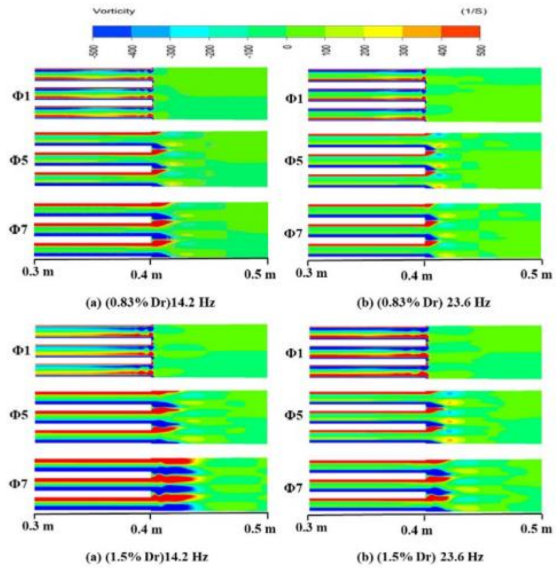

Figure 2. Vortex structure within and at the end of the plate for three different drive ratio

General Review on Velocity Profile Measurement

Acoustic velocity in a thermoacoustic system can also be measured experimentally using several methods. The experiment methods that will be discussed in this paper are Hot-Wire Anemometry (HWA), Laser Doppler Anemometry (LDA), and Particle Image Velocimetry (PIV). Prior researchers commonly used these three methods in experimentally measuring acoustic velocity in thermoacoustic systems.

The mechanism of HWA starts when an electrically heated wire is placed in a flowing gas stream, where heat is transferred from the wire to the gas, causing the wire's temperature to reduce and, due to this, the resistance of the wire also changes. The change in the resistance of the wire is used to measure the flow rate or velocity. HWA is widely used for measuring flow velocity and turbulence since it provides an accurate and compact anemometer for low velocity continuous flows, and it is also easy to install and cost-effective compared to LDA and PIV. Jerbi et al. (Jerbi et al., 2013) adopted the HWA method in measuring acoustic velocity based on acoustic pressure measurement via their relationship using a linear acoustic model. The result in this paper stated that due to the difference in the heat transfer between the oscillating fluid and the hot-wire, the velocity either increases towards the resonance or decreases beyond it. This follows the law of the acoustic velocity amplitude whereby it is not continuous when the resonance frequency is crossed. This result was supported by

Elger and Adam (Elger & Adam, 1989), who affirmed that HWA in the oscillating flows requires dynamic calibration because dynamic heat transfer differs from steady-flow heat transfer.

LDA is a measurement system consisting of two coherent laser beams that intersect to form a series of interference fringes where fluid velocity is to be measured (Yaacob & Velte, 2021). A tracer particle suspended in the fluid passes through these fringes. The intensity of the light scattered from the particle is modulated at a frequency proportional to the spatial component of particle velocity that is normal to the fringes. The movement of the tracer particle is assumed to follow the motion of the fluid. The scattered light is collected by a receiver lens and focused on a photodetector. The scattered light contains a Doppler shift, known as the Doppler frequency (fD), which is proportional to the velocity component and perpendicular to the bisector of the two laser beams. The photodetector converts the fluctuating light intensity into electrical signals, and through several processors, the velocity of the flow is provided.

Bailliet et al. (Bailliet et al., 2000) examined the acoustic power flow in the resonator tube using LDA and microphonic measurement. This measurement setup enables the plotting of the velocity profile and pressure measurement inside the resonator tube. The outcome of this setup aligns with the analytical results. In this work, the size is taken at 4 cm from the loudspeaker, the total length of the resonator is 49.7 cm, and the stack center position is located 14 cm from the loudspeaker. Thus, the results did not represent the stack component's velocity and pressure profiles at entry, inside, and exit. Meanwhile, Thompson and Atchley (Thompson et al., 2005) adapted LDA and burst spectrum analysis (BSA) to investigate the acoustic streaming generated in a cylindrical standing wave resonator filled with air. It is observed that LDA/BSA generated a significant error in the time-averaged velocity-signal component. Due to the error, Lagrangian streaming velocities are determined using the time-harmonic signal components and the arrival time of the velocity component, and the results align with Rott's theory. Again, in this study, the stack component is not considered in the experiment setup; thus, the results are only valid when using an empty resonator tube.

Particle Image Velocimetry (PIV) is an optical measurement technique whereby the velocity field of an entire region within the flow is measured simultaneously. PIV uses the displacement of the particle image in the plane as the measurement principle to determine the displacement of the particle in the flow. The most common way for measuring displacement is by dividing the image from the two-time exposures. A typical PIV setup includes a high-speed camera, a high-power multi-pulse laser, an optical arrangement to convert laser output light sheet, and a synchroniser that controls the synchronisation between the laser and the camera. Figure 3 shows the common setup of a PIV measurement.

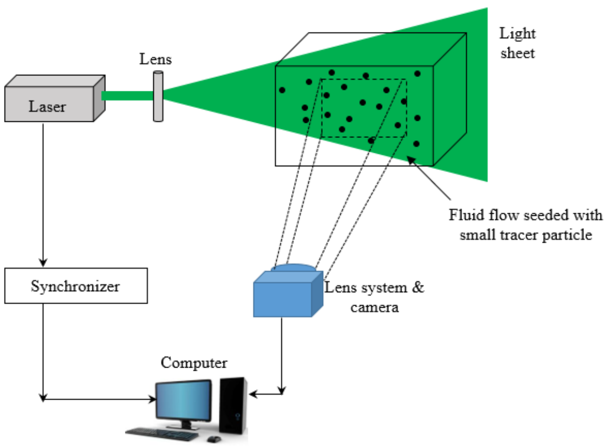

Figure 3. Schematic diagram of a PIV setup

The lack of heat transfer correlations for oscillatory flow led Shi et al. (Shi et al., 2010b) to use PIV and Planar Laser-Induced Fluorescence (PLIF) to measure time-resolved temperature and velocity fields in the thermoacoustic system. PIV alone can only measure velocity, but with the addition of PLIF, it can measure the temperature in the region. Since the test rig includes a microphone, the pressure data was recorded during the experiment. The results show that there is an overshoot in velocity and temperature distribution. The velocity overshoot is due to the viscous and inertial effect in the gas, while the overshoot of temperature is caused by the velocity overshoot and the combined effect of the viscous and thermal boundary layers. This result highlights the strong relationship between velocity and temperature fields in the thermoacoustic system, as shown in

Figure 4. In other works done by Shi et al. (Shi et al., 2010a), PIV was used to identify a range of vortex shedding flow patterns at the end of parallel-plate thermoacoustic stacks based on the effect of Reynolds number (Re), Keulegan-Carpenter number (KC), and Womersley number (Wo). It is found that Wo plays an essential role in determining the detailed classification of such transitions within each flow pattern region. Another work done by Shi and his team on oscillatory flow patterns can be found in (Shi et al., 2011).

Zhang et al. (Zhang et al., 2019) applied PIV in measuring the oscillatory flow at the end of the thermoacoustic parallel plate. In this study, Zhang and his team experimented with and without the stack using two different resonator lengths to indicate different fundamental frequencies. The results show that heat transfer enhancement is due to increased resonator length. Therefore, decreasing the fundamental frequency and increasing the velocity amplitude enlarges the ejection vortices.

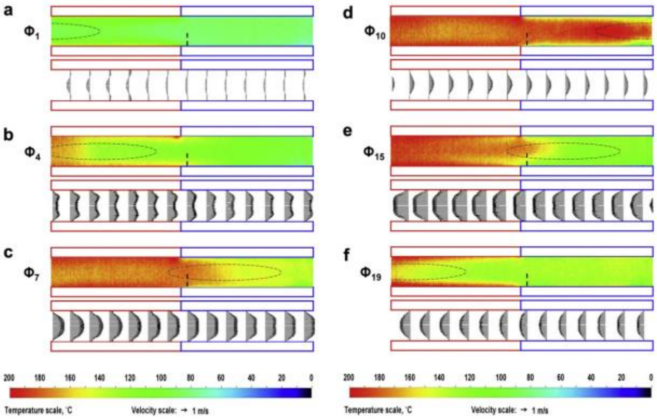

Figure 4. Temperature and velocity distributions for six selected phases in an acoustic cycle (Shi et al., 2010b)

Discussion on Velocity Measurement Methods

Since velocity and pressure distribution determine the heat transfer rate in the thermoacoustic system, researchers must investigate the characteristics of the velocity profile inside the resonator tube with the existence of the stack component. The lack of correlation that represents the oscillatory flow for thermoacoustic systems, as stated by Shi et al. (Shi et al., 2010a), is the main issue that requires solving. For simulation-based methods, when comparing CFD and DeltaEC, DeltaEC has the advantage of solving the problem in a short time and still gives reliable results since it is consistent throughout the experiment. However, the main drawback is that the software has a minimal ability to detect turbulence and streaming flow, which is crucial in investigating oscillatory flow. Meanwhile, CFD showed its ability to illustrate the streaming effect, as reported by Mohd Saat et al. (Mohd Saat et al., 2019) and Allafi et al. (Almukhtar Allafi et al., 2021), (Almukhtar et al., 2020).

To confirm the outcome of the simulation works, an experiment must be done to evaluate the result to the real application system. HWA has the simplest setup compared to LDA and PIV. It has advantages in terms of no seeding required in the flow and provides a relatively high temporal resolution of the acquired signal. HWA can also identify velocity fluctuations related to vortex shedding at the stack's entrance and exit, as Mao et al. reported (Mao et al., 2008). However, to cover the flow region, the probe must be relocated a thousand times to collect the data for the whole system, which is troublesome considering the tight space at the stack and heat exchanger. In addition, HWA is the only invasive method, as the probe needs to be inserted into the resonator. Even though it is stated that the probe will have the minimum effect on the flow, it will also introduce another error that adds leakage while running the experiment.

Meanwhile, the LDA method can measure acoustic velocity and acoustic power flow with a good spatial resolution (Bailliet et al., 2000), but evidently, the LDA method is not suitable to be applied in the thermoacoustic system due to the difficulties of introducing a convergent laser beam in the tight space. For PIV measurement, this method enables the visualisation of the velocity distribution inside the resonator tube and can detect the streaming effect at the entrance and exit of the stack, as reported by Shi et al. (Shi et al., 2010a). The PIV method can also record temperature parameters if the PIV system adds on the PLIF component. These benefits make it the preferred experimental method compared to LDA and HWA. However, PIV requires several components in the setup; hence, this method can be costly.

Conclusion

In conclusion, every measurement method has its advantages and drawbacks. For velocity measurement for oscillatory flow in thermoacoustic systems, CFD is the preferred simulation-based method compared to DeltaEC because of its ability to detect turbulence and streaming in the flow. Thus, the reason why the majority of the researchers conducted their research using the CFD method. Meanwhile, for experimental-based methods, PIV showed significant advances compared to HWA and LDA in terms of its ability to visualise the oscillatory flow with the streaming effect in the thermoacoustic system. Even so, there are minimal studies that were conducted using this particular method. This shows the vast opportunities for researchers to investigate further the characteristics of the velocity profile in the oscillatory flow for thermoacoustic devices.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to authors.

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