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Flow Pattern Analysis for Oscillatory Flow inside Resonator Tube for Thermoacoustic Refrigerator Using PIV Measurement

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Abstract: A thermoacoustic refrigerator system is an alternative cooling system that uses air or inert gas as a cooling fluid. The environmentally friendly characteristics make this system potential as a green alternative for a cooling system. However, due to its low efficiency compared to conventional vapor compression systems, its application is limited. Since a thermoacoustic refrigerator is based on the oscillatory flow to generate a cooling effect, the understanding of a flow pattern inside the resonator tube is crucial to enhance the coefficient of performance (COP) of the system. In this study, Particle Image Velocimetry (PIV) is used to visualize the flow pattern inside the resonator tube. PIV is an optical, noninvasive technique that uses a high-speed camera, high-power multipulse laser, and synchronizer to capture the particle movement in the resonator with a length of 1 m, and the frequency applied is 100 Hz. The result shows that there is a formation of a vortex at the entrance and at the exit of the stack. The formation of the vortex at the entrance induces by the flow disturbance created by the stack. This vortex formation varied with the location of the stack and the amplitude of the wave applied. The velocity distribution of the particle inside the resonator tube is also presented and discussed in this paper. These findings indicate that the flow patterns and velocity distribution should be further analyzed to interpret the effect of these characteristics on the system. These results are expected to give a better understanding of the future development of the thermoacoustic system.

Keywords: Thermoacoustic, Flow pattern, Velocity distribution, PIV

Introduction

Thermoacoustic refrigeration (TAR) showed potential as an alternative for the cooling system. (L. Xiao et al., 2022) The environmentally friendly characteristics make this technology a desirable alternative method. The limitation of TAR to being commercialized or practically used widely is due to its low efficiency compared to conventional vapor compression systems(Chase, 1995), (Girgin & Türker, 2012),(Swift, 2017),(Biwa, 2021). Most of the researchers focus on the stack, which is the main component in TAR to improve efficiency(Alamir, 2019),(Babu & Sherjin, 2018), (Ilori et al., 2021). But, since the working principle of TAR is based on the oscillatory flow-powered sound wave, there is a minimal study that discussed the flow characteristics inside the resonator tube (Berson et al., 2008). Analyzing the acoustic flow, such as flow pattern and velocity distribution, is crucial to understand the behavior of the oscillatory flow inside the tube and then relate it with the heat transfer process. Understanding how heat is transmitted may help to boost the system's efficiency.

Recent studies by Allafi et al., 2021 found that the vortex appears where heat is transferred (Almukhtar Allafi et al., 2021). The appearance of the vortex may be influencing heat transfer. This phenomenon is owing to the oscillatory flow's ability to facilitate heat transfer. A vortex would create a black hole in which heat transmission is impossible. Therefore, an oscillatory flow that is smooth and fluid would be more advantageous. Additionally, Zhang et al. (2013) also found the development near the end of the stack and concluded that the emergence of the vortex impacts pressure and velocity. (D. W. Zhang et al., 2013). As the formation of vortex is observed by (Almukhtar Allafi et al., 2021)and (Hireche et al., 2020), the current theoretical formulation by Rott is the linear theory of acoustic that assumes the flow is laminar may create the deviation between theoretical study with the actual system. Hence, studying the relation between oscillatory flow and the heat transfer process inside a resonator tube is crucial. Thus, the efficiency of the overall system can be improved.

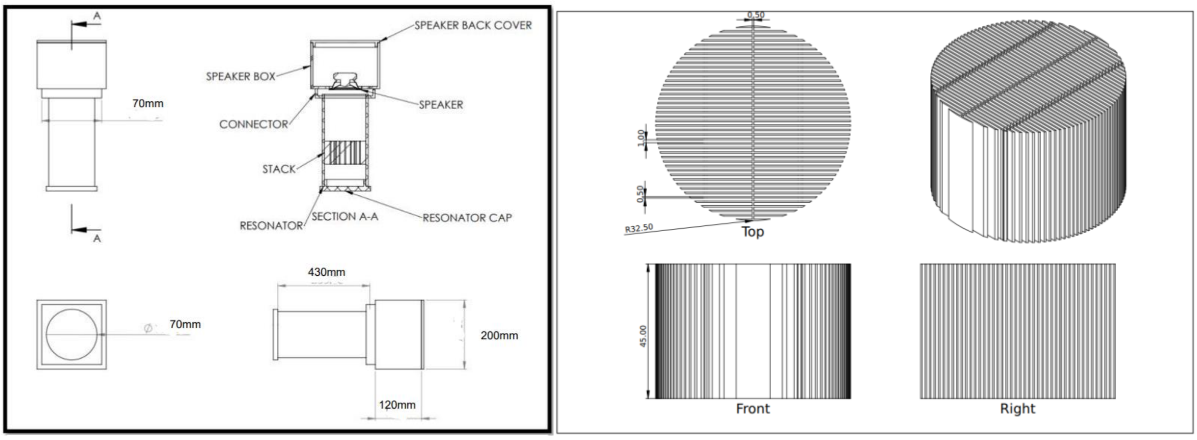
There are several possible ways of obtaining reliable flow characteristic information (velocity profile, temperature distribution, and pressure) to perform detailed quantitative measurements for a thermoacoustic system. The methods that used in past researches for measuring velocity profiles are divided 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) methods to determine the velocity profiles. Meanwhile, for experimental-based, there are three methods that 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, majority of the researchers (X. Xiao et al., 2020), (Mohd Saat et al., 2019), (Abd El-Rahman et al., 2017) prefer to conduct research using simulation-based methods, especially the CFD method compared to experiment-based.Thus, the flow characteristic of thermocoustic system limited to the simulation data compared to the actual phenomenon. This may be due to the high cost of having to set up the experiment rig that involves certain components, especially for PIV and LDA setup.

For LDA systems are used by scientists and business professionals to better understand fluid dynamics. Using the measurement data, product designs may be fine-tuned to increase aerodynamic effectiveness, quality, and safety. Bailliet and co are the only groups that study the flow measurement in a resonator of TAR by using LDA. From LDA, they have taken note of the pressure and velocity of flow in the resonator. Then, validate by using an analytical method. Since the error is less than 8%, the result from the experiment is agreeable with the analytical. It showed that LDA is proved a good technique for study flow.(Bailliet et al., 2000). However, Zhang (2002) found LDA bias in the flow measurement (Z. Zhang, 2002). By using past raw data of TAR in 1D, 2D and 3D, he compared it with numerical which calculated. As result, the mean velocity was constant in all measured data. This showed that LDA is biased as turbulence influences the measurement.

Meanwhile, PIV is a technique that studies the velocity vector measurement by measuring the movement of particles between two image frames. This image was captured by the camera in between two light pulses (laser). In 2012, Blanc and his colleague investigate the effect of the vortex on heat transfer by using PIV. They used an acoustic pressure at 500Pa and 2500Pa. As result, they found out that the emergence vortex increases, and this phenomenon effecting of additional heating despite want loss of heat (Blanc-Benona et al., 2012). To evaluate acoustic and streaming in a thermoacoustic system, Debesse and his friend used undersample PIV measurement. By using different data processing tool in PIV, they found that when acoustic wave intensity increases, irregular streaming appear (Debesse et al., 2014). In 2020, Hireche and co study the generated convection flow in the thermoacoustic device by using PIV experimentally and also in simulation. They used all the thermoacoustic core with and also without a heat exchanger. As result, it was found that natural convection flow is significant that it affects the thermoacoustic effects (Hireche et al., 2020). From the past studies, it can be seen that using PIV in experiments helped researchers find multiple data that related to the flow. In TAR, even a slight change in parameters of the system allows multiple studies can be observed like Zhang et. al. Thus, this paper will study the flow pattern and velocity distribution inside the resonator in thermoacoustic system using PIV measurement.

Experimental Setup Using PIV

The standing wave thermoacoustic device contains a resonator with a length of 43 cm. The thermoacoustic device also contains a stack, a speaker for acoustics as shown in Figure 1a). The stack is designed to fit the resonance tube and is made from Acrylonitrile butadiene styrene (ABS) material using a 3D printer as shown in Figure 1b). 3D printer is chosen because it is more precise, and time saving compared to other alternative choices. The material selected for this stack should have low thermal conductivity. The thermal conductivity of the stack material has a negative impact on the performance of the thermoacoustic refrigerator. If the thermal conductivity of the stack material is high, the heat which has been pumped by the system will be conducted back to the cold side, thus reversing the cooling effect. Thus, ABS was chosen since it has low thermal conductivity. ABS was used for the stack material because of the good balance of impact, chemical, dimensional stability, tensile strength, surface hardness and is also rigid. The designed stack has a diameter of 65 mm, and the length of the stack is 45 mm. Each plate in the stack has a thickness of 0.5 mm while the distance between each plate is precisely 1 mm. The plate is given spacing to also the movement of acoustic frequency and heat. This shape is chosen because of the as to study the acoustic particle velocity via a particle image velocimetry.



a) b)

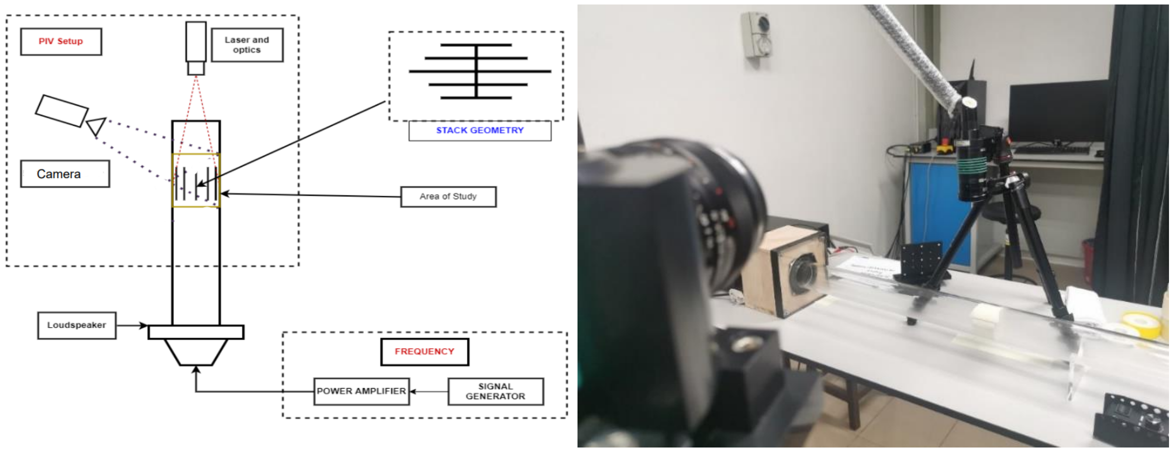
Figure 1. a) Schematic diagram of TAR system b) Schematic diagram of stack

The components required for PIV setup is illustrated in Figure 2 for schematic and actual components. The laser beam is generated by a dual-resonator Nd: YAG laser with a wavelength of 532 nm. The laser has a repetition rate of 15 Hz. The laser energy could reach 135 mJ with an energy stability of 2 %. This is powerful enough to illuminate the seeding particles. The laser is placed on top of transparent rectangular lance to light the view window area. The light beam optical lens has 40 cm to the upper wall of the resonator. The short duration of light pulse is 5e7 ns, and the time between two laser pulses changes with the velocity which effectively freezes the particle position. The system uses a singular camera system for the PIV. The camera is a IMPERX ICL-B1620 with 1600 X 1200 pixels and 14-bit resolution CCD sensor, The camera lens is Nikon AF-S VR MICRO-NIKKOR 105 mm on the camera which is installed on a multi axis tripod with a 1:2.8 D lenses.

In PIV measurements, the velocity of the particles suspended in the flow is observed and measured by using seeding particles which serves as the "velocity indicator." The particles must be in appropriate size so that the flow can be accurately observed, and sufficient light can be scattered for the camera to detect them. The particles should be buoyant in the flow, and their density should be approximately the same as that of the fluid. Three types of particles are considered as seeding particles: the glass beads, the incense granules, and fog of silicone oil. Among them, the glass beads can be easily bonded to the plexiglass wall and the incense smoke is difficulty to control. As a result, the measurement plane is seeded with oil fog generated by a fog generator in the test.

Before the ejection of the droplet, the fog generator had a heating stage for about 20 minutes. The oil fog is then injected into the resonator before turning the loudspeaker on and is added at any time if the particle concentration is reduced. The particles are generated automatically with diameters ranging from 1 to 3 mm. The acoustic oscillation makes seeding particles homogeneous in the resonator and measurement of the velocity particles in the test bench could be performed.

In the measurement, the CCD camera has 60 frames per second at full resolution and the maximum laser frequency is 15 Hz; The laser frequency is lower than the frequency of the oscillation flow. Thus, it is not possible to shoot the images of the different phases in one cycle. To overcome this problem, a phase averaging method by phase locking technology is employed to acquire the images. First, the velocity signal near the resonator close end is transformed to square wave signal with the same frequency. Then, the converted signal is adjusted by the function generator and becomes TTL signal. In this procedure, the acoustic cycle is subdivided in 24 equally spaced phases. The adjusted signal triggers the laser and the camera to acquire the same phase of the cycles. Instantaneous velocity fields are acquired for each phase and averaged to obtain a phase-averaged velocity field. The PIV data processing software, dynamic studio v3.4 is used to determine the velocity maps. Based on past PIV research, the study area should be small enough so that no significant velocity gradient is present within the study area.



a) b)

Figure 2. a) Schematic diagram of TAR system with PIV b) Actual experiment setup with TAR system and PIV

Attachment of TAR System with PIV Measurement

To conduct the experiment, the thermoacoustic device is placed in front of the PIV measurement device. To do this a few steps need to be executed. Firstly, the camera and laser need to align exactly to the position where the stack will be placed. To do this a calibration plate is needed. A calibration plate is a series of evenly dotted lines which represents the 2-dimensional plane of the study area. The calibration area should exactly be the size of the study area, so that during the alignment process the cameras can be aligned properly. As we know the dimension of the stack is 65mm x 45mm. So, the calibration plate will be 65mm x 65 mm in size. The extra 20 mm is to see the behaviour of the airflow during the entrance and the exit from the stack.

Next is the camera and laser alignment. For this step the calibration plate is first placed in the position where the stack (study area) will be placed. For this experiment the calibration plate is placed about 30 mm deep of the stack so that all the stack fins can be measured. This position is also chosen due to the bridge in the middle of the stack which holds all the plates together. The laser is then aligned until it is in the same plane as the calibration plate. This step is important so that only particles at that plane is measured and not obstructed by the bridge in the middle of the stack. Next, the camera is then aligned to fit picture perfectly the study area which now being represented by the calibration plate. The multi axis tripod of the camera is adjusted to get the perfect position in Z-axis, Y-axis, and X-axis. The camera angle should also be adjusted to fit perfectly on the calibration plate. The measurement of the camera tripod from home position is as follows: -

X-axis – 358.00 mm
Y-axis – 0.00 mm
Z-axis – 400.00 mm

After this step, the alignment of the camera and laser is validated by using the dynamic studio v3.4 software. If the alignment is perfect, then the calibration plate position is marked and replaced with the thermoacoustic test rig. The position of the study is validated again so that no errors occur during the experiment. For this experiment, the variable that needs to fixed is the frequency of the acoustic flow. To decide this, we need to consider the past study and the capabilities of the existing thermoacoustic resonator. As stated, before the existing thermoacoustic device was designed for a 20Hz acoustic frequency. The 20Hz is selected because the whole thermoacoustic device is built in mind with that frequency.

Result and Discussion

Flow Pattern inside Thermoacoustic Resonator

Figure 3(a), (b), (c), and (d) show the flow formation inside the resonator tube from t = 0 until t = 1s. The black box is showing the location of the stack inside the resonator tube. From the flow pattern captured by PIV, there are several important observation can be made. Firstly, as the loudspekar is turn on, the velocity of the air is increasing as the effect of the acoustic sound wave inside the resonator. Then, as the sound wave entering the stack, there are increament of air velocity at the entrance and induce the vortex formation. This observation supported by the previous study conducted by Allafi et al., 2021 that oscillatory flow past parallel plate structures creates significant vortex structures at the entrance and at the end of plates. The formation of the vortex also stronger at the end of plates as the flow changes direction after reflected at the end of the resonator. The air velocity between the parallel plate of the stack is equal with the velocity of the air before the entrance velocity. As the air leaving the stack, the air velocity increasing again as air is escaping from narrow gap between stack plate and can be observed from the figure, there are formation of the significant vortex at the exit of the stack. This finding is crucial and need to further investigation since the flow pattern will effect the heat transfer process between plate and the working fluid. This result also suggests that there maybe enough instabilities present in the flow to trigger turbulent transition.

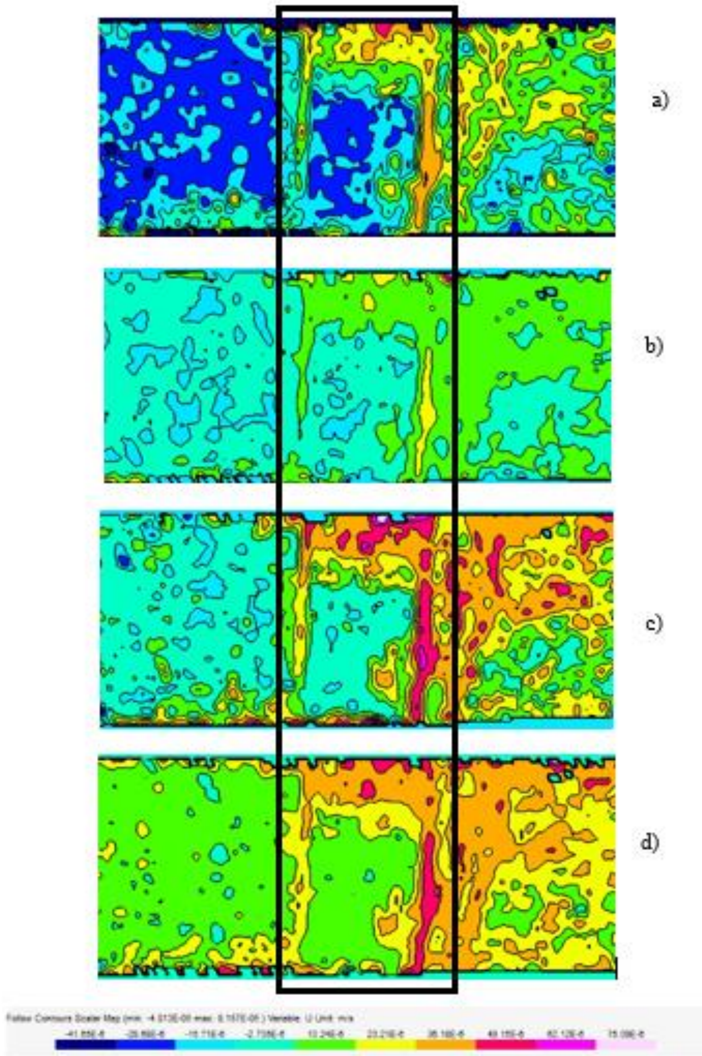


Figure 3. Flow pattern inside resonator when a) t = 0 s b) t = 0.333 s c) t = 0.667 s d) t = 1.00 s after the loudspeaker is turn on

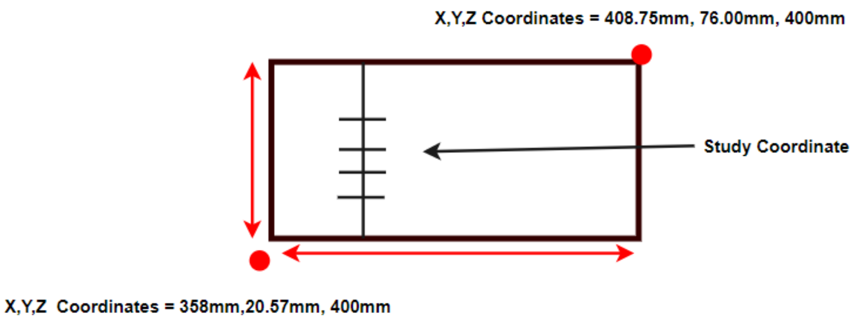


Figure 4. Study area in the resonator tube

Velocity Distribution in Thermoacoustic Resonator

To understand better about the results we need to understand the coordinates of the study area. The coordinate of the study is dependent on the home position of the camera rig. The study area coordinate starts from coordinates X= 358mm, Y= 20.57mm, and Z= 400mm. The study area is also in a rectangular shape due to the camera frame. The other end of the study area is X = 408.75mm, Y = 76.00 mm and Z = 400mm as shown in Figure 4, noted that the velocity distribution that will be discussed in this section only presenting the velocity at the entrance of the stack and the value of the velocity is an average value for particles captured by PIV measurement system.

For this analysis multiple coordinates in x coordinate over varying Y coordinate are chosen to study the difference in the flow pattern and differentiate the velocity profile. For a better understanding of the results and graphs the position of stack is quite important. The stack is at X coordinate 390 mm. The graph from Figure 5 (a) shows a harmonic flow pattern as the coordinates are in front of the stack region. The graph in figure 5(b) is bit different as it has higher Y velocity causing an unusual pattern in the resultant velocity. The formation of the flow pattern due to the disturbance of flow from large space to the narrow space, the spacing of the stack plate is 0.5mm which is narrow enough to form the vortex at the entrance of stack. In Figure 5(c) the point 4 and 2 shows the maximum velocity of 0.0595 m/s and 0.0565 m/s. This is because the flow just went past around the stack and create vortex formation at the entrance of the stack. This produces high velocity at both boundaries of stack. For Figure 5, it can be observec that only one point has a maximum velocity of 0.0439 m/s. By comparing the velocity of the flow in y direction for every x coordinate, it is observed in Figure 5(a), 5(b), and 5(c) the velocity at point 3 shows the minimum velocity which is at the middle point in y-coordinate for the stack. This may be due to the design of the stack that have structure support of the stack plate. The support of the stack completely blocks the flow thus it creates sudden velocity drop at that location.

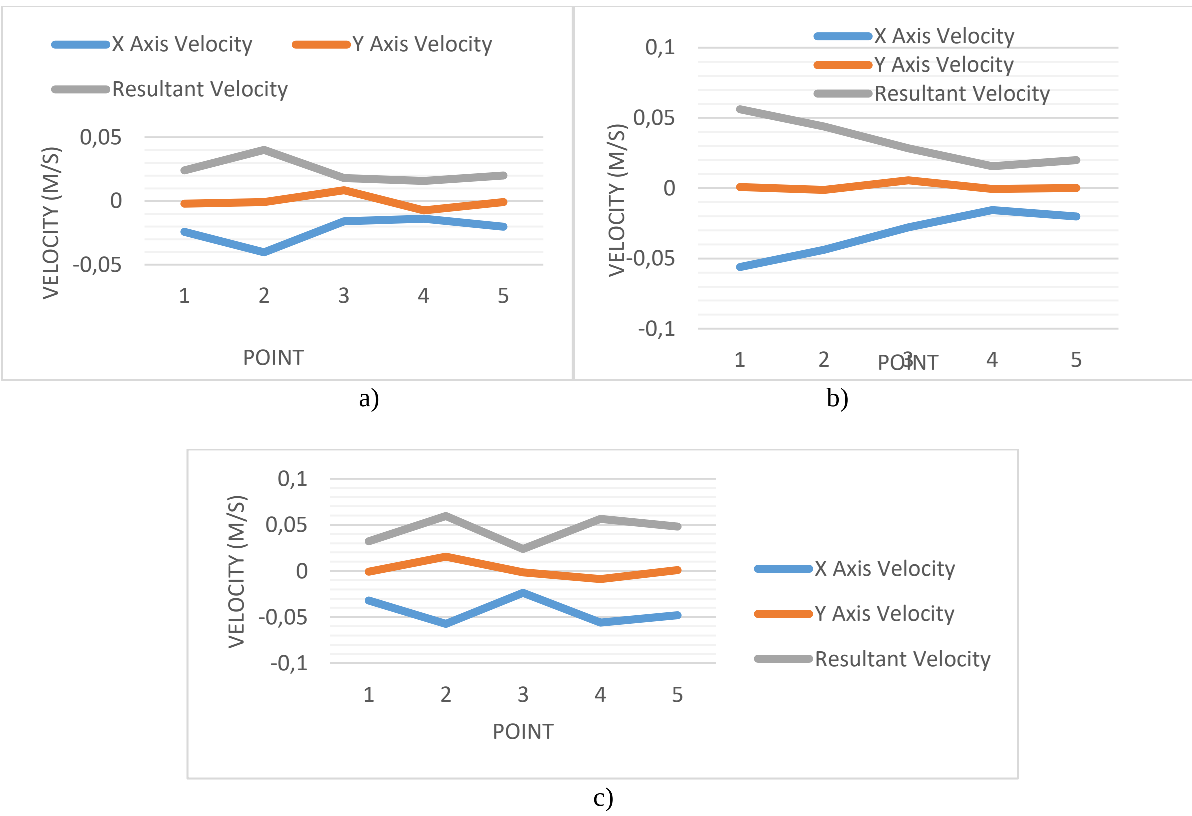
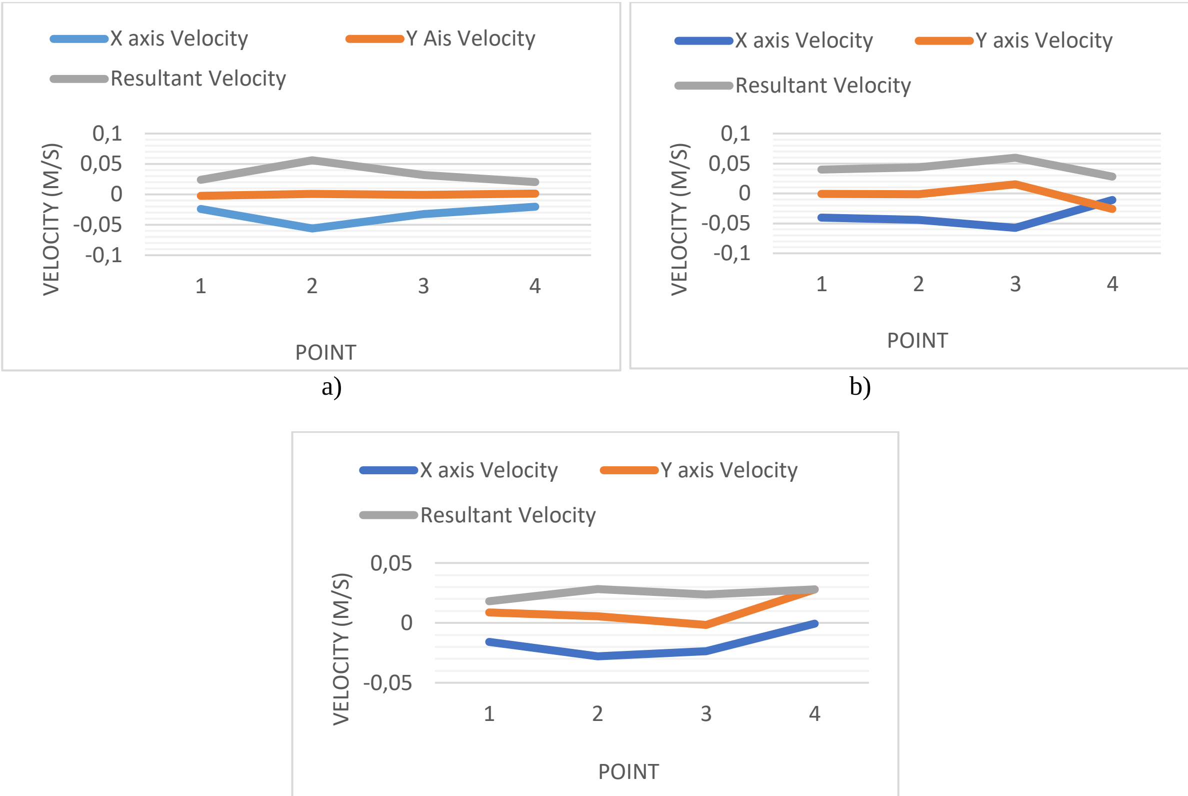


Figure 5. Velocity measurement when a) X axis is 372.43 mm b) X axis is 384.05 c) X axis is 395.68 mm

For this study multiple coordinates in Y coordinate over varying X coordinate are chosen to study the difference in the flow pattern and differentiate the velocity profile. For a better understanding of the results and graphs the position of stack is quite important. The stack is at X coordinate 390 mm. From Figure 6(a), 6(b), and 6(c) the point 1 and 2 are in a incline straight line showing a harmonic oscillatory flow because it is in front of the stack. Velocity of point 3 in Figure 6(b) which is 0.0595 m/s is quite high compared to point 3 and 4 in other figures indicating that the flow just went past around the stack and create vortex formation at the entrance of the stack. This produces high velocity at both boundaries of stack. By comparing the velocity of the flow in y direction for every X coordinate, it is shown that the point 2 and 3 in the Figures 6(a), 6(b), and 6(c) show a higher resultant velocity of particle movement compared to point 1 and 4. This is caused by the vortex flow phenomena. Vortex flow reduces the pressure behind the stack and has a high velocity. This can be clearly seen in the graph trend. The velocity in Figure 6 is in the range of 0.018 m/s to 0.0283 m/s which is the minimum value for all three graphs. This may be due to the design of the stack that have structure support of the stack plate. The support of the stack completely blocks the flow thus it creates sudden velocity drop at that location.



c)

Figure 6. Velocity measurement when a) Y axis is 20.57 mm b) Y axis is 35.11 mm c) Y axis is 48.19 mm

Conclusion

This experiment was done with the purpose of understanding the flow pattern of oscillatory flow and the effect of stack on the flow pattern in the thermoacoustic refrigerator. From the results of the experiment a lot has been understood regarding the flow pattern in a thermoacoustic refrigerator. From the experiment, the flow in the front of stack is known to be harmonic and linear. From the same result obtained, it can be concluded that the flow pattern of the oscillating flow forms vortex flows after the stack region. This is because it can also be clearly noticed that the acoustic flow separates from the stack on its two downstream sides, and, as the boundary layer becomes detached and curls back on itself, the fluid forms vortices. At the entrance of the stack the flow also creates vortex formation. The formation of the flow pattern might be due to the disturbance of flow from large space to the narrow space. The spacing of the stack plate is 0.5 mm which is narrow enough to form the vortex at the entrance of stack. At the middle of the stack, the velocity is minimum. This may be due to the design of the stack that have structure support of the stack plate. The support of the stack completely blocks the flow thus it creates sudden velocity drop at that location.

Scientific Ethics Declaration

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

Acknowledgements or Notes

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