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Investigating Effect of Geometric Differences on Fluid Behavior in Synthetic Jets

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Abstract

A synthetic jet is a flow that is created by an actuator vibrating at a specific frequency and amplitude. In this study the velocities and propagation of synthetic jets have been measured using both circular and single-wave orifice geometries. Axial velocity measurements in the direction of flow have been taken using the PCE 423 model hot wire anemometer. Also flow visualization has been performed using TiO_2 surface oil visualization to determine velocity distributions in the radial direction. The measurements have been conducted at different H/D values, representing the ratio between the axial distance (H) and the orifice diameter (D). The excitation frequency has been varied between 4 Hz and 5 Hz with a sinusoidal signal type. The results have shown that circular orifice geometry have higher velocities in the axial direction. However, When the axial velocity was measured at 4 Hz, it has been observed that the single wave geometry provided results close to a circle at H/D = 13 and 14 values, and at 5 Hz for H/D = 12 and 13 values. This suggests that the geometric shape is not very important at high H/D ratios. In addition, the axial velocity values for a single wave orifice geometry show almost the close results for both excitation frequency values. The flow visualization results have indicated that the single-wave orifice geometry with H/D=12 ratio perform better and provides a more accurate and well-distributed velocity field. In conclusion, the findings of this study suggest that synthetic jets could be potentially useful for industrial applications, especially in heat transfer applications with their extended flow field implications.

Keywords: Synthetic jet, Hot wire anemometer, Flow visualization, Single wave orifice, Excitation frequency, Flow control technique.

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Sentetik Jetlerde Geometrik Farklılıkların Akış Davranışı Üzerine Etkisinin İncelenmesi

Öz

Sentetik jet, belirli bir frekansta ve genlikte titreşen bir aktüatör tarafından oluşturulan bir akıştır. Bu çalışmada, dairesel ve tek dalga orifis geometrileri kullanılarak sentetik jetlerin hızları ve yayılımı ölçülmüştür. Akış yönünde eksenel hız ölçümleri PCE 423 model sıcak tel anemometresi kullanılarak alınmıştır. Ayrıca, TiO_2 yüzey yağ görselleştirmesi kullanılarak radyal yöndeki hız dağılımlarını belirlemek için akış görselleştirme yapılmıştır. Ölçümler, eksenel mesafe (H) ve orifis çapı (D) arasındaki oranı temsil eden farklı H/D değerlerinde gerçekleştirilmiştir. Uyarma frekansı sinüs sinyal tipi ile 4 Hz ve 5 Hz arasında değiştirilmiştir. Sonuçlar, dairesel orifis geometrisinin eksenel yönde daha yüksek hızlara sahip olduğunu göstermiştir. Ancak, eksenel hız 4 Hz'de ölçüldüğünde, tek dalga geometrisinin H/D = 13 ve 14 değerlerinde daireye yakın sonuçlar verdiği, 5 Hz'de ise H/D = 12 ve 13 değerlerinde benzer sonuçlar sağladığı gözlemlenmiştir. Bu, yüksek H/D oranlarında geometrik şeklin çok önemli olmadığını düşündürmektedir. Ayrıca, tek dalga orifis geometrisi için eksenel hız değerleri, her iki uyarma frekansı için neredeyse aynı sonuçlar vermiştir. Akış görselleştirme sonuçları, H/D = 12 oranı için tek dalga orifis geometrisinin daha iyi performans gösterdiğini ve daha doğru ve iyi dağılmış bir hız alanı sağladığını göstermiştir. Sonuç olarak, bu çalışmanın bulguları, sentetik jetlerin özellikle geniş akış alanı etkileriyle ısı transferi uygulamalarında potansiyel olarak kullanışlı olabileceğini göstermektedir.

Anahtar Kelimeler: Sentetik jet, Sıcak tel anemometresi, Akış görselleştirme, Tek dalga orifis, Uyarma frekansı, Akış kontrol tekniği

1. INTRODUCTION

A synthetic jet is a type of flow that is created by a fluid or gas being blown out of a small cavity. This flow generates vortices or swirling motions in the surrounding fluid or gas and can be used to produce a controlled flow or to manipulate the airflow around a surface. The fluid or gas is alternately blown out and sucked back into the actuator, creating a cyclical flow pattern. This flow pattern can be used to control the airflow around a surface by altering the pressure distribution on the surface. Synthetic jets are used in various sectors such as aviation, energy, and industrial processes for applications such as flow control and mixing. Additionally, synthetic jets can effectively cool electronic devices that generate high heat. In this study, synthetic jet is created with a moving membrane by generating a closed volume with a small opening on the loudspeaker. It is aimed to experimentally examine the variation of the synthetic jet flow characteristics depending on the orifice shape and to determine the synthetic jet characteristics.

Tesar and Kordik [1] used a mathematical model for synthetic jet actuators which produces a jet flow or gas through a small cavity. They used a quasi-similarity approach, which involves scaling the problem to reduce the number of independent variables, in order to simplify the model. Then, they use this model to investigate the behavior of synthetic jets in various conditions, such as changes in the amplitude and frequency of the actuator. It is reported that the quasi-similarity approach was a useful tool for modeling synthetic jets, as it allows for the investigation of a wide range of parameters with relatively simple models. They also suggested that their model can be used to optimize the design of synthetic jet actuators for specific applications. Tesar and Kordik [2] used Fourier analysis to examine the power spectral density of synthetic jets and compared it to that of natural jets. They also investigated the effect of various parameters, such as jet frequency, amplitude, and Reynolds number, on the spectral characteristics of synthetic jets. Their results showed that synthetic jets exhibit distinct spectral characteristics that differ from those of natural jets. Furthermore, it is observed that synthetic jets produce a broadband spectrum of frequencies, which may have important implications for their potential applications in flow control and noise reduction. Oren and Gutmark [3] investigated the flow characteristics of non-circular synthetic jets with a vibrating diaphragm. They focused on the effects of various parameters, such as the aspect ratio, the actuation frequency, and the Reynolds number, on the flow characteristics of the synthetic jets. They used both experimental and numerical methods to study the flow characteristics of the synthetic jets. Particle image velocimetry (PIV) was used to measure the velocity field of the flow. The results of the study showed that the flow characteristics of non-circular synthetic jets are significantly influenced by the aspect ratio, actuation frequency, and Reynolds number. It was observed that the formation of vortex rings in the flow, which is important for understanding the underlying physics of the generated jet flow. Travnicek et. al. [4] defined a study on the visualization of synthetic jet formation in air. Synthetic jets were devices that produced a pulsating flow of fluid or gas, and they had a variety of applications in areas such as cooling and ventilation. They used particle image velocimetry and shadowgraph techniques to visualize the formation of synthetic jets in air. They studied the behavior of synthetic jets produced by different actuator shapes, including circular, rectangular, and triangular. The results showed that the actuator shape has a significant effect on the formation and behavior of the synthetic jet, with the triangular actuator producing the most efficient jet. Crispo et. al. [5] explained an experimental study of the flow field produced by a chevron synthetic jet actuator. They investigated the effect of changing the operating parameters of the actuator, including the oscillation frequency, amplitude, and duty cycle, on the resulting flow field. The study reveals that the flow field produced by the chevron synthetic jet actuator is complex and includes multiple vortex structures with different sizes and intensities. They also observed that the actuator's operating parameters have a significant impact on the flow field's characteristics, such as the position and strength of the vortex structures. Feero et. al. [6] tried cylindrical, conical and contraction (curvilinearly contracting) models in their study, in which they examined the effect of the change in void structure on synthetic jet performance. They stated that the radial velocity profiles were the same in the three models, but their magnitudes were different. In terms of mean momentum fluxes, they revealed that it is highest in the cylindrical and lowest curvilinear contraction model. In addition, they explained that the curvilinear constrictive model consumes less power at the point where the cavity oscillation reaches its peak and has the highest efficiency in oscillation. Rylatt and O'Donovan [7] experimentally studied the effect of a confined synthetic jet with and without channels on heat transfer. The channel output diameter was adjusted to 1.2, 1.6 and 2, and its effects on the results were examined. In their study, they changed the dimensionless Stroke length (L0/D=15) the Reynolds number to 3000 (Re=3000), and the jet-to-surface distance to H/D= 0.5-3. Provides the greatest increase in heat transfer at H/D = 1. They explained that the reason for adding a channel was to eliminate the effects of both quasi-constraint and restraint. Bhapkar et. al. [8] investigated the acoustic and heat transfer characteristics of an impinging elliptical synthetic jet generated by an acoustic actuator. They experimentally studied the influence of various parameters on the flow field and heat transfer rate, including the geometry of the orifice, actuation frequency, and amplitude. They found that the elliptical synthetic jet can provide better heat transfer performance than traditional circular jets, and that the performance can be further improved by adjusting the actuation parameters. The studied suggests that synthetic jets can be a promising approach for enhancing heat transfer in various applications, and that the elliptical geometry may be a preferred shape for improving performance. Ghaffari et. al. [9] investigated the flow and heat transfer characteristics of a slot-impinging synthetic jet. They have scanned the local flow field using PIV, a particle imaging technique. Synthetic jets are a type of airflow created by a fluctuating motion generated in a cavity bounded by a diaphragm. Using different air velocities, jet exit angles, and jet/nozzle spacings, the effects of synthetic jets on the slot surface were examined. The experiments showed that the maximum cooling performance was associated with a spray-surface gap of 5≤H/D≤10. It is stated that it does not show full consistency in heat transfer at close jet surface gap distance such as H/D=2. Additionally, the jet exit angle and jet/nozzle spacing were observed to have a significant effect on the flow and heat transfer characteristics of the synthetic jet on the slot surface. For a constant Reynolds number, the cooling is increased at high Stokes numbers, but the coefficient of performance is decreased. The experimental study by Travnicek and Tesar [10] is on circular synthetic jet production and its control. This active flow control system is designed with a synthetic jet with a nozzle. Synthetic jets are driven with pulse modulation. In their experiments, two different flow areas are observed. One of them is with the bubbles form a small circulation zone and the other have a large circulation zone. They showed that the wall pressure and heat transfer take place towards the center at the stopping point in one and outward from the rest point in the other. Mangate and Chaudhari [11] examined the impinging of the multiplying multi-orifice structure on cooling performance. In the study, different configurations of multiple circular holes were tested. They found that the maximum heat transfer coefficient obtained with the multi-orifice synthetic jet is higher than the conventional single-hole synthetic jet. In the cost calculation, they said that the multiplying multi-orifice synthetic jet is a cheaper cooling than a fan. Lee et. al. [12] investigated the effects of rectangular aperture for the synthetic jet with an experimental setup using a loudspeaker and acrylic sheets. They tested three rectangular orifice shapes with two different hydraulic diameters (4 mm and 8 mm) and two aspect ratios (4 and 8) as well as four different cavity sizes. Actuator jet exit velocity was measured from the outlet plate at positions 2, 4, 6, and 8. The frequency and Reynolds number were changed to determine the combination that would provide the most heat transfer in the tested configurations. As a result, they explained that very shallow cavities have a negative effect on the jet velocity and the best heat transfer results are obtained in orifices with a larger hydraulic diameter with a smaller aspect ratio. Gil and Strzelczyk [13] investigated the momentum velocity associated with the actuator release frequency, the Reynolds number, the force applied to the actuator, and different gap configurations. They defined the ratio of the kinetic power of the flow based on the momentum velocity as the efficiency of the synthetic jet actuator. They revealed that the maximum efficiency is close to the speaker resonance frequency or the Helmholtz frequency. They showed in their experimental studies that the maximum efficiency depends on the geometry of the actuator, that is, the geometric structure of the internal volume. Hong et. al. [14] worked on the parameters that affect the synthetic jet characteristic. They showed that the edge configuration influences the eddy ring, such as mass flow rate and jet efficiency. At the same time, they found that the distortions in the jets are high when the orifice geometry is not a circle. In addition, regarding the aspect ratio, which is the parameter affecting the characteristic, they found that a higher aspect ratio will result in higher jet output. Greco et. al. [15] compared the twin-hole synthetic jet actuator with the conventional single-hole in this study and examined the Reynolds number as 5100 and the Strouhal number as 0.024. For a single jet, the axial velocity profile near the plate at short distances to the blast table showed a double peak near the jet axis. At high nozzle-plate distance, they revealed that the axial velocity profile is bell-shaped. Comparison of the two synthetic jet configurations found higher axial velocity and lower axial phase-correlation with turbulence level for the twin case due to the interaction of the jets. In addition, the saddle point in the suction phase showed a different structure in both configurations. Wang et. al. [16] investigated jet characteristics and heat transfer in orifice structures with non-circular square, rectangular and elliptical geometry. It has been found that the orifice configuration has a significant effect on the heat transfer performance of an impinging synthetic jet by influencing the eddy behavior. They found that the heat transfer increased in elliptical and rectangular orifices compared to the circular structure. At the same time, double peak temperature distribution was detected in rectangular geometry with AR value of 5.

As can be seen in the literature summaries above, studies regarding flow characteristics have been carried out for many geometries such as triangle, square, rectangle, circle, multiple circles, elliptical. The effects of orifice geometry on the flow characteristics have been examined in these studies. As a result of these investigations, an orifice geometry that has not been tried before in the literature has been studied in this study. The aim of this study is to contribute to fulfill the gap in the literature.

2. MATERIAL AND METHOD

A synthetic jet flow has been generated using a loudspeaker type actuator by utilizing the desired frequency structure. The flow characteristics of the obtained synthetic jet have been examined. A hot-wire anemometer has been used to measure the velocity of the flow for different orifice geometries in generating the synthetic jet flow. Two different orifice structures have been determined, one being circular geometry and the other being a single-wave structure that has not been previously encountered in the literature. To examine the flow field, the surface of a plexiglass plate has been visualized with TiO_2-coated oil. A plexiglass cover has been placed on the top surface of the speaker to provide a closed volume. The flow is transmitted to the orifice exit in a laminar manner thanks to the pipe used. The orifice geometry used is a single wave structure with a width of 2 mm. Orifice geometries have been produced using PLA on a 3D printer.

2.1. General Description of Experimental Setup

In this study, sine wave type signals with frequencies of 4 Hz and 5 Hz and output amplitudes of 4 Vpp have been sent from the signal generator to the synthetic jet actuator. The schematic description of the experimental setup has been shown in Figure 1. First, the signal from the signal generator has been amplified in a voltage amplifier. A DC power supply has been connected to the system to provide power to the voltage amplifier. The amplified signal has been sent to the loudspeaker. The synthetic jet flow has been generated depending on the structure and output geometry of the synthetic jet actuator, including the loudspeaker. Adjustable arms have been designed to adjust the probe position at the desired H/D ratio. This has allowed for easy up and down movement of the probe. A hot wire anemometer has been used for velocity measurement. The values have been read from the digital display. The general schematic description of the experimental setup has been shown in Figure 2.

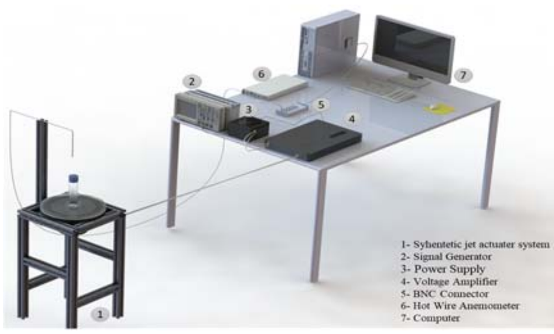


Figure 1. Solid model schematic view of the experimental setup

Figure 2. Photographic description of experimental setup

The PCE 423 model hot wire anemometer shown in Figure 3 has been used to measure the linear flow velocity of the synthetic jet generated by the loudspeaker. The moving parts designed for the probe movement have also been shown in the same figure.

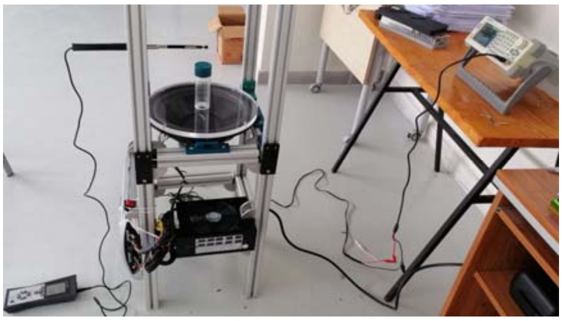
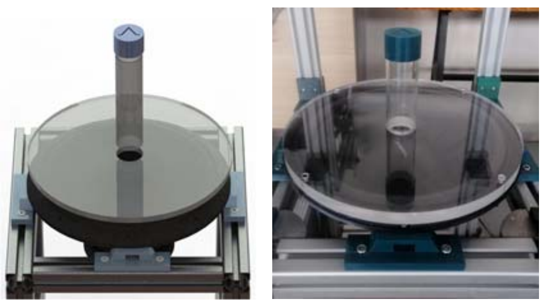


Figure 3. Schematic representation of the velocity measurement system with using hot wire anemometer

2.2. Synthetic Jet Actuator Design

The components that made up the synthetic jet generation system have been shown in Figure 4. A Jameson Brand JW-36 model 1200 W loudspeaker with an outer diameter of 30.5 cm and an inner diameter of 29.5 cm has been used. A 15 mm thick plexiglass cover has been placed over the loudspeaker to create a closed volume. A 40 mm diameter pipe has been tightly fitted and fixed to the plexiglass cover. 4 parts have been designed using a 3D printer to secure the loudspeaker to the sigma profile, thus reducing the effect of vibration on the loudspeaker from the sigma profile. The plexiglass sheet has been produced using a 3-axis CNC router to bring it to the desired dimensions.



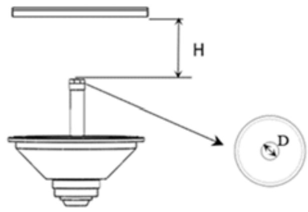


Figure 4. Shematic and photographic description of the loudspeaker system

2.3. Orifice Geometry Design

The orifice geometry designed for placement on the pipe has been a single wave shape, as shown in Figure 5, which has been compared to a circle (Figure 6). The dimensions of the orifice geometries have been shown in detail in the technical drawing in Figure 7. The inner diameter of the geometry that has passed through the pipe has been determined to be 39.98 mm. Its outer diameter has been 43.98 mm. The diameter of the circle has been determined to be 11 mm, with an area of 95 mm^2. The center of the circle has been taken as a basis for designing the single wave geometry orifice. In addition, the width of the area where the flow exits in the single wave geometry orifice has been determined to be 2 mm. The total exit area in the geometry has been designed to be the same as that of the circle (95 mm^2). As a result, the exit areas of both geometries have been kept constant.

Figure 5. Orifice shape of single wave

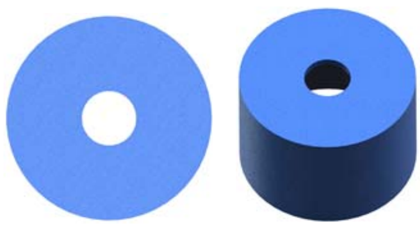


Figure 6. Orifice shape of base model

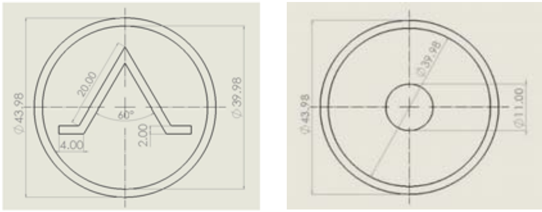


Figure 7. Technical drawing of orifice shapes

As seen in Figure 8, two tree brand 3D printers were used to produce orifice geometries.

Figure 8. Production of orifice shapes by using 3D printer

2.4. Flow Visualization Setup

The signal, which is generated from a signal generator with a 4 Hz frequency and 4 Vpp sinusoidal signal structure, has been amplified in an amplifier and then sent to the speakers. The setup used for flow visualization is shown in Figure 9. First, a square plexiglass plate with dimensions of 30cmx30cm and a thickness of 4 mm has been used. This plate has been painted black using spray paint. Then, the surface has been painted with a TiO_2 plate using the oil visualization technique. This plate has been placed in the direction of the synthetic jet flow as shown in Figure 9. The synthetic jet flow, which is obtained from the speaker, has been achieved by spraying it onto the plexiglass plate coated with TiO_2 at a certain H/D ratio.

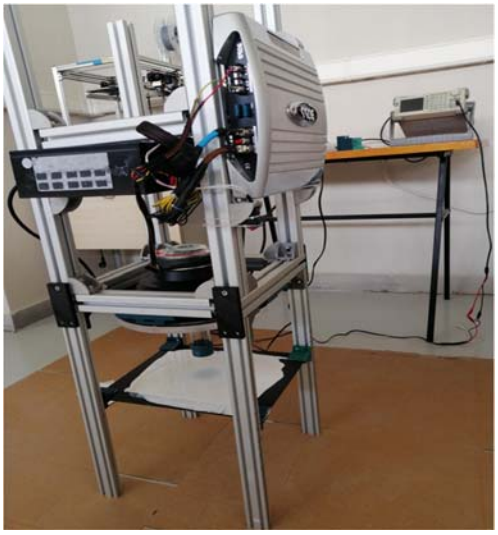


Figure 9. Schematic description of experimental setup for flow visualization

3. RESULTS

A synthetic jet is a type of flow produced using a loudspeaker or similar device. This jet may look like a real jet and may resemble a real jet in some of its properties. In this study, SJ flow was obtained by using a speaker type actuator. Velocity measurement and flow visualization were performed in the axial direction using different orifice structures.

3.1. Axial Velocity Experiment Results

Measurements have been made of the axial flow at a given H/D ratio when the air has been released through the loudspeaker. The PCE 423 model hot wire anemometer has been used to make the axial measurement with sinusoidal signal structures of 4 Hz and 5 Hz frequency. With this device, the air flow rate has been calculated by measuring the change in wire temperature caused by the air flow. In this way, accurate results have been obtained even at low velocities. Axial velocity has expressed the velocity of the air moving along the duct, while radial velocity has expressed the velocity of the air around the duct. When the axial velocity is high, it shows that air moves faster through duct. In this case, the exposed synthetic jet may have had a longer range. However, greater axial velocity may have caused the synthetic jet to mix less with the surrounding air, meaning that the air has not been more homogeneous in the circumferential direction as seen in Figure 12. When the frequency was increased to 5 Hz (Figure 11), although there was a slight increase in velocity in the circular orifice, the single-wave geometry orifice produced results similar to those at 4 Hz. This suggests that the single-wave geometry provides a more homogeneous fluid distribution, which is also supported by flow visualization results (Figure 12). However, when the velocity measurements in the axial direction at 4 Hz and 5 Hz have been examined, it has been seen that the single wave geometry has given results close to the circle in increasing H/D values. Especially when looking at the velocity measurement at 4 Hz (Figure 10), it has been seen that the single wave geometry has given results close to a circle at H/D =13 and 14 values, and at 5Hz (Figure 11) H/D =12 and 13 values. For this reason, it can be said that the geometric shape has not been very important at high H/D ratios.

The velocity has been measured at 4.2 m/s for the single wave orifice structure at a probe position of H/D=4, while it has been 5.7 m/s for the circular orifice. It has been seen in the graphs in Figure 10 and Figure 11 that while this value has decreased linearly in the circle, it has progressed almost constantly in the other orifice's form. These results have shown that the single wave orifice design has operated at slower speeds than the circular orifice design. However, it may have indicated that the performance of the single wave-shaped orifice has been less efficient than the circular orifice or has exhibited different flow characteristics.

Although the single wave geometry orifice has a smaller outlet area, the total outlet areas are the same as the circle. However, the single wave geometry orifice has given fewer velocity measurement results than the circular orifice. The single wave geometry orifice has a sharper edge than the circular geometry orifice. This sharp edge can cause more energy loss during the acceleration of the fluid. Additionally, the single wave geometry orifice has changed the direction of the fluid more, which can cause velocity loss. In contrast, the orifice in a circular geometry has changed the direction of the fluid less and therefore has caused less velocity loss. Therefore, the lower exit velocity of the single-wave orifice can have been explained by the effect of geometrical properties. Also, as the orifice cross-sectional area has widened, the velocity has been expected to have decreased, but the change in velocity has been limited until a certain diameter value because the increased outlet area has reduced local losses.

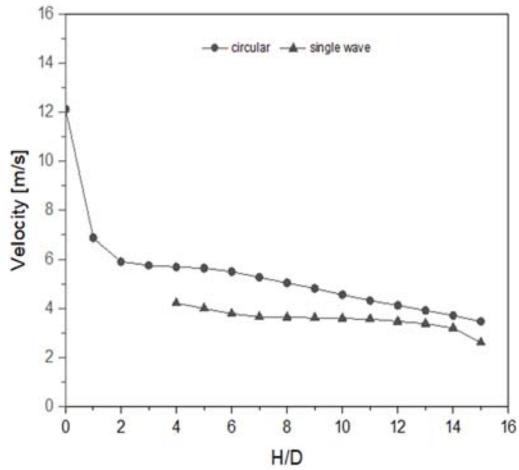


Figure 10. Velocity measurement results at 4 Hz frequency in axial direction

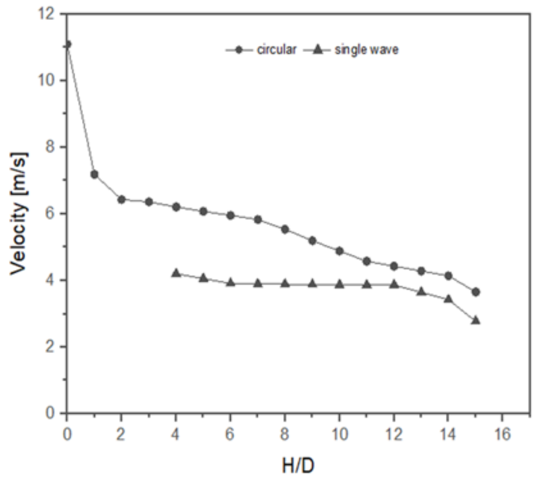
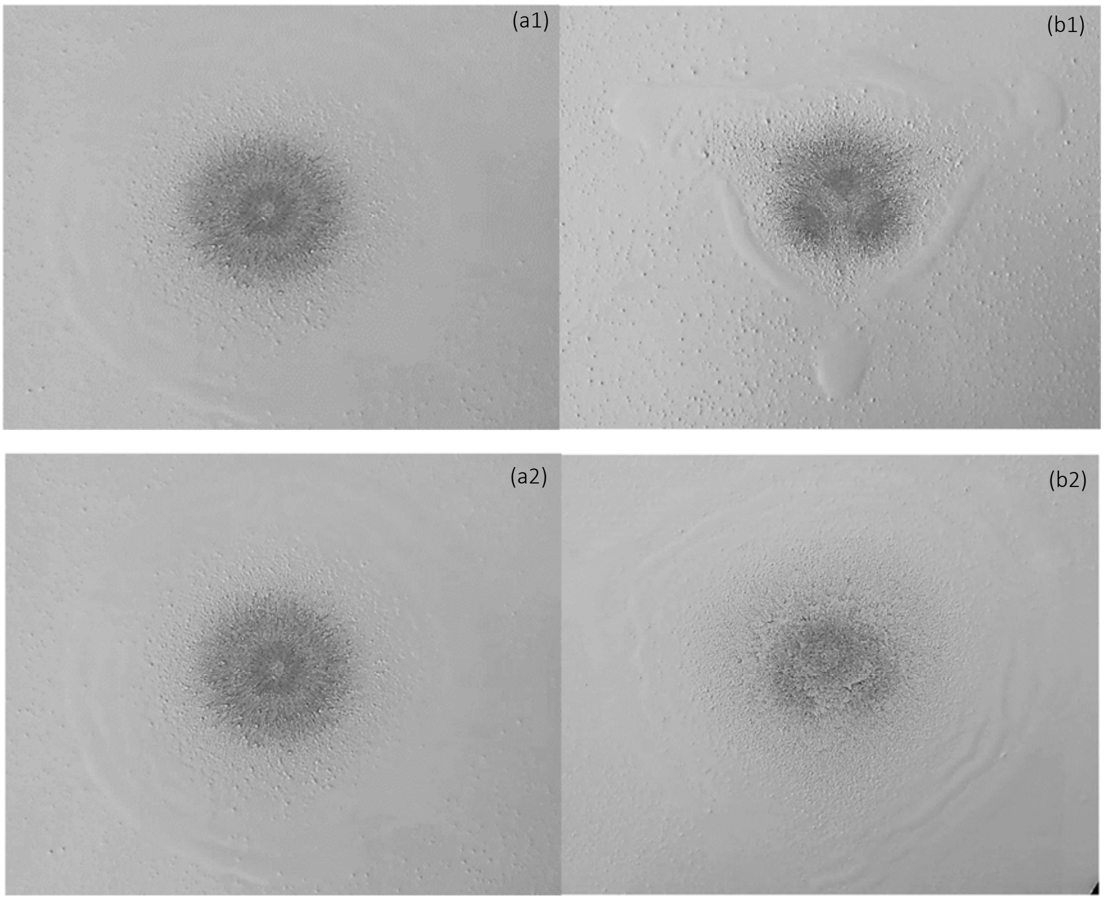


Figure 11. Velocity measurement results at 5 Hz frequency in axial direction

3.2. Flow Visualization Experiment Results

The flow visualization results have helped to improve our understanding of the design characteristics and fluid behavior. The difference in velocity distribution in the radial direction indicates that the single-wave orifice design exhibits a different fluid behavior. Figure 12 compares the flow visualization results of the circle and single wave orifice shapes at different positions of H/D (H/D= 3, 6, 9, 12 and 15). Looking at the flow visualization results, it has been observed that the velocities and propagation patterns in the radial direction have varied according to the single wave and circular orifice geometry at different H/D ratios. Especially, in the ratio H/D = 3 of the plate position, the distribution of velocities in the radial direction has differed in the orifice with a single wave geometry compared to the circular geometry. Although the impact areas have been the same, a triangular spread has been observed in the single wave geometry while a more circular spread has been observed in the circular geometry. This can provide an advantage for using the single wave orifice in applications that require more precise control. If H/D = 6, the impact area has been observed to be more layered in the single wave orifice compared to the circular orifice, based on the flow visualization results. These results may provide an advantage depending on the specific application requirements. The velocity and propagation patterns in the radial direction can be important factors in certain applications.



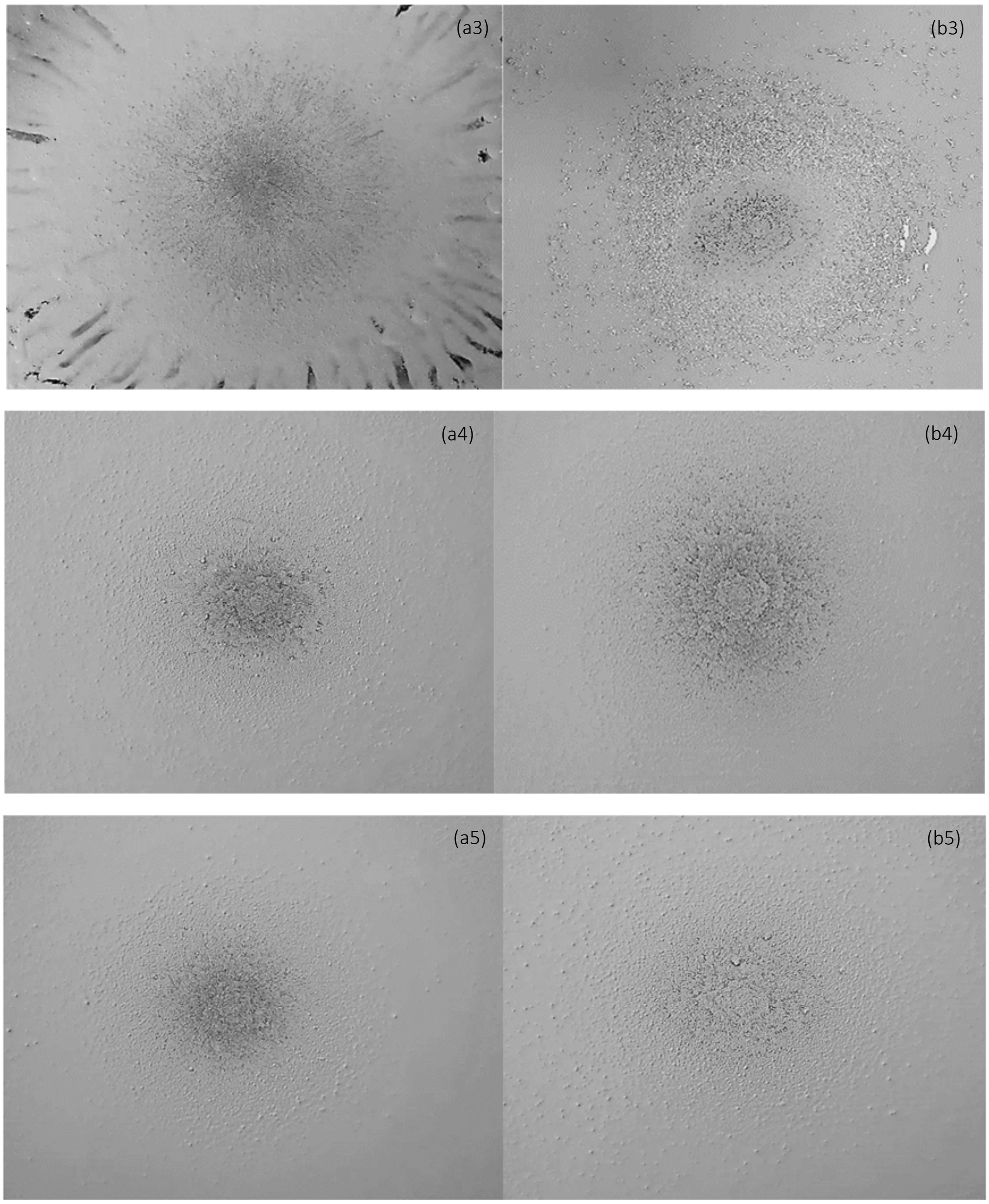


Figure 12. Flow visualization of circular (a1-a5) and single wave (b1-b5) geometry orifice shapes where H/D is 3,6,9,12 and 15, respectively

An increase in the H/D value has meant an increase in the distance of the fluid around the orifice. Therefore, at higher H/D values, the diffusion of the fluid takes place over a larger area. This also applies to the single wave geometry orifice design, and the larger the area of influence of this design, the greater the dispersion of the fluid. This can increase the performance of the design in a particular application area. However, there has been a velocity difference between two different orifice designs that have shown a similar spread (circular) at higher H/D values, which may indicate that one design has been more efficient due to the geometry. It has been seen that the most efficient ratio in the orifice design is H/D = 12 and the single wave orifice design has more area of influence than the circular orifice.

The use of single-wave orifices may have been beneficial, particularly in applications where low-speed fluids need to be mixed, such as ventilation systems, heating/cooling systems, and industrial chemical processes. A single wave orifice design may have been a potential candidate for heat transfer systems. It may have been useful, particularly in places where air needs to be distributed. This design may have efficiently regulated the flow with a larger impact area and greater dispersion, helping to filter out unwanted substances such as dust, metal particles and etc. At an H/D ratio of 12, it may have been seen to be more effective than the circle orifice in terms of radial distribution, which may have helped distribute the fluids used in heat transfer applications more effectively. However, the suitability of the design for cooling applications may have depended on the characteristics and requirements of the application.

4. DISCUSSION AND CONCLUSION

Synthetic jets are typically generated using a loudspeaker, an actuator that provides membrane movement. The loudspeaker moves at a specific frequency and amplitude controlled by an amplifier, which induces the formation of a synthetic jet flow. In this study, a synthetic jet actuator has been designed using a speaker, and axial velocity measurement and flow visualization have been performed using a new orifice. The effects of circular and single-wave geometry orifices with different H/D ratios on fluid behavior have been examined. Based on the results of the axial velocity, the orifice with single-wave geometry moves steadily at a lower velocity than the circular geometry. The velocity in the circular geometry decreases linearly. The flow visualization results indicate that the orifice with single-wave geometry performs better at certain H/D ratios. At H/D = 3, a triangular spreading is observed at the plate position for the single wave geometry, while a more circular spreading is observed for the circular geometry (Figure 12). This suggests that the single wave orifice geometry could be used in applications that require more sensitivity. Also it has been found that the orifice with single-wave geometry is more efficient, especially at an H/D ratio of 12. According to presented results, it can be considered that orifices with single-wave geometry may be more effective in heat transfer applications.

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