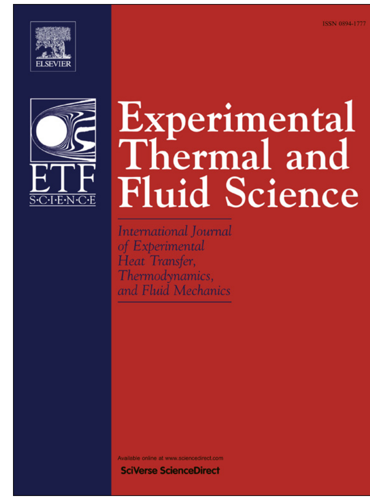

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Experimental Study of formation and development of Coherent Vortical Structures in Pulsed turbulent Impinging jet

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ABSTRACT

Coherent structures play a crucial role in enhancement of convective transport phenomena. An experimental investigation was carried out to study the effect of jet flow oscillation on the characteristics of vortex structures in a turbulent confined circular impinging jet. Effects of key parameters such as frequency of pulsation and type of excitation on the development of shear layer coherent vortical structures in time and space and their dynamics were studied using the smoke-wire technique and high speed photography. Results of this study show that flow pulsation in a circular impinging jet leads to the periodic formation of coherent vortical structures which are larger than those in steady impinging jets. Pulsation frequency has significant effects on the formation and size of structures and consequently their dynamics. At higher frequencies, vortex structures are formed in a regular inline pattern and as a result the mixing between the jet fluid and stagnant fluid is reduced. For the step (rectangular) signal shape larger vortices are created in comparison with those in sinusoidal one. The results of flow visualization show that enhanced mixing and transport rates will be achieved for turbulent impinging jets that excited with "step" signal shape.

Keywords: Coherent Vortical Structures, Flow Pulsation, Impinging Jet, Transport Phenomena

Nomenclature

A	Amplitude of Pulsation (dimensionless= $\frac{U_{max}-U_0}{U_0}\times 100$)
B_w	Transvers distance between vortex cores (m)
D	Nozzle Diameter (m)
f	Pulsation frequency (Hz)
H	nozzle-to-surface spacing, [m]
L	Longitude of nozzle cylinder (m)
L_h	instant distance of vortex core from nozzle exit (m)
Re	Reynolds number (= $\frac{\rho U_0 D}{\mu}$)
St	Strouhal number (= $\frac{fD}{U_0}$)
T	Pulsation period (s)
T	Time (s)
$U(t)$	Instant Jet velocity at inlet , (ms^{-1})
U_0	Average air velocity at inlet (ms^{-1})
U_{max}	Maximum velocity (ms^{-1})
x, y	Coordinates (m)

1. INTRODUCTION

Impinging jets are commonly encountered in chemical, food, electronics, pulp and papers, etc., industries with wide applications for cooling, heating, and drying in which the main concern is increasing the rates of transport processes. Formation of vortical structures and their dynamics lead to significant effects on mixing, flow instability and transport processes. Crow and Champagne [1] studied coherent vortical structures in a turbulent flow and discussed the critical role of these structures and their fundamental role in engineering phenomena. There is a general agreement on this issue that these vortical structures have important effect on the rate of transport phenomena. Since turbulence energy production and transfer occurs in larger structures and energy dissipation occurs in the small structures, investigating the quality and dynamical characteristics of these structures can provide fundamental understanding of their effect on heat and mass transfer.

According to previous studies it can be inferred that fluid flow domain of an impinging jet can be divided into four main zones viz. initial mixing region, established jet, deflection zone, and wall jet [2-5]. Each one of these regions plays an important role in practical uses such as mixing of fuel and air in combustion chambers, jet ejectors, noise reduction, etc. Numerous computational and experimental studies have been carried out to examine these phenomena [6]. The flow characteristics of impinging jets are related to the situation that the entering jet experiences. Vortices are formed initially by Kelvin-Helmholtz instabilities [7]; then vortices merge in the developing region. Thus, heat transfer and flow characteristics of impinging jets can be controlled by managing vortices using active or passive means. Parameters such as geometry (nozzle shape, distance from nozzle to plate, and plate shape), working fluid, Reynolds number, and turbulence intensity are in the passive category. On the other hand, flow features can be controlled dynamically in the active methods. Recently, one of the most interesting active methods to affect the rate of transport phenomena is flow pulsation. Jet excitation commonly refers to the introduction of time dependent disturbances to the inflow to stimulate the primary instabilities of the shear layer. The most prevalent type of excitation is that of acoustic pulsation method where a loudspeaker is applied to excite the primary shear layer structures with acoustical pressure/velocity disturbances. By altering the pulsation signal characteristics such as signal frequency, amplitude and phase difference, scientists have clarified that formation pattern and size of vortical structures can be precisely controlled in impinging jets configuration [8]. The effect of pulsation excitation on flow characteristics of a circular impinging jet is investigated experimentally by Vejrazka and Tihon [9]. The jet is excited by a time dependent sinusoidal signal. The phase-averaging method is applied to study the behavior of coherent vortical structures in the shear layer of the jet; specifically the formation, merging, and collision with the wall. Their results showed that vortex collision on the wall leads to an unsteady flow separation. Cvetinovic et al. [10] studied experimentally the flow field of the turbulent air jet that excited acoustically by a periodic and harmonic pulsation signal. The Main goal of their investigation was to observe the coherent vortical structures of turbulent air jet issuing from the nozzle of special configuration. Their flow visualization results for the excited and non-excited air jets showed that flow pattern has very high sensitivity to the excitation frequency.

Nevins and Ball [11] considered heat transfer between a flat plate and a pulsating impinging jet and showed that there is no significant difference between a pulsating jet and a steady one. Their tests were carried out for $1,200<Re<120,000$, $10^{-4}<St<10^{-2}$, and aspect ratio (H/D) between 8 and 32. They did not mention secondary vortices and their experiments were limited to low Strouhal Numbers. Due to this work published, research in pulsating impinging jets was abandoned for almost 25 years. In the late 80's and early 90's several research groups started to work on pulsating flows again. Many numerical studies have been carried out since those days by several researchers. In those studies, the effects of various parameters such as Reynolds number, H/D, number of nozzles, type of pulsation function, frequency, and amplitude have been investigated [12-20]. Kataoka and Suguro revealed the critical role of secondary flow structures in determining the rate of heat transfer [21]. They also showed that heat transfer in the stagnation region is affected mainly by large structures and existence of these large structures is reported in pulsating jets. In addition to this fact (periodic formation of vortices that face the hot surface), pulsating flows cause boundary layer to be thinner. The boundary layer disappears periodically and then reforms for step type function of pulsation. Mladin and Zumbrunnen [22] investigated the effects of pulsating function type, frequency and amplitude on mean and instant convectional heat transfer of a flat plate theoretically and by means of a boundary layer model. They noted that there is a critical Strouhal Number (St=0.26) below which there would be no significant change in the rate of heat transfer.

Turbulent flows are consist of different eddies with widespread time and size spectrum. Computational fluid dynamics scientists assert that turbulent kinetic energy production and transportation are related to coherent structures of the flow. There are different kinds of these structures which are named by their appearance (e.g. horse show, hairpin, twin, vortex sheet, and vortex tube). Crow and Champagne [1] showed that these vortical structures are formed in the shearing layer of a circular jet. They also reported that these vortical structures can make more coherent and larger by acoustic excitation near St=0.3. Changing the flow patterns in the entering stream affects the flow field and the turbulence mixing phenomena. Lio et. al. [23] visualized a pulsating rectangular jet of low aspect ratio and low frequencies at high amplitudes by means of hydrogen bubbles. They claimed that vortices' span-wise drift at higher amplitudes and frequencies is distinct and detectable. The convection velocity of the vortices increases at lower frequencies and higher amplitudes. They did not consider the buoyancy effect of hydrogen bubbles in the water flow and their investigations were limited to Re=1300. As a more general case, Hwang et. al. [24] mentioned an important concept in impinging jets which is vortex pairing. They claimed that this phenomenon will diminished at higher Strouhal numbers which are in the range of 1.2-4 and delay the jet development region. As a result, the jet experiences longer potential core and lower turbulence intensity in the jet core region.

Studying the effects of external excitations on formation of coherent structures and their dynamics in impinging jets had almost been abandoned. There is a serious gap in extracting coherent structures and their interactions according to the impingement surface. By accepting this fact, investigating the effects of these parameters on coherent vortical structures in a circular impinging jet is considered as the main scope of this study.

This study aims to visualize the vortical structures in a pulsating impinging jet with different external excitations by means of smoke wire technique and high-speed camera. Then, interpretation of flow behavior according to different circumstances of entering flow is presented. The jet is excited with a load speaker at different Strouhal numbers. First, the test rig is described. Then, results for the reference case which is the steady impinging jet is presented. These results are then compared to the results of pulsating impinging jet with sinusoidal type of excitation. After that, effects of various frequencies of excitation and two types of excitation function (sinusoidal and step) are investigated. Finally, kinematic behavior of vortical structures in a circular pulsating impinging jet is extracted and technical interpretation is presented.

2. EXPERIMENTAL APPARATUS

All steady and pulsed jets investigated issued from the same longitudinal cylinder made of glass with a diameter (D) 100 mm and a length to diameter ratio (L/D) of 10. Experiments and flow visualization were carried out in a large room with ambient air at rest. Schematic diagram of experimental setup is shown in figure 1. A 2-cylinder compressor which can provide 248 liter air per minute, connected to a 250 liter high-pressure tank is the air source for the experiment. The air passes through a water-air heat exchanger to minimize fluctuations of air temperature during the experiment. The design of equipment is based on the open circuit wind tunnel, which includes a diffuser, settling chamber, screens, and a contraction section. The nozzle section is circular and its diameter is constant along the jet axis. A well-designed settling chamber is mounted upstream of the jet to dampen the fluctuations generated by the compressor. Its dimensions are selected big enough to reduce the rate of air changing per hour to 5. The "settling chamber" or "stilling section" is the largest cross section, and contains a honeycomb and/or screen. Two sets of fine screens are mounted in the settling chamber to reduce turbulence intensity to an acceptable level. A honeycomb with its cells aligned in the flow direction which will reduce mean or fluctuating variations in transverse velocity (flow direction) is mounted immediately after screens, with little effect on stream wise velocity. Because the pressure drop through a honeycomb is small. Woven-wire screens mainly reduce stream wise velocity fluctuations, with little effect on flow direction. Then, the stream splits into two circular channels going to the main jet and it is similar to the one were used by Anderson and Longmire [25]. A guide vane, a honeycomb, and a fine screen are installed in the air line to manage the flow quality, which is very important to investigate phenomena related to upstream conditions. The Reynolds number based on the jet exit diameter (D) and mean air exit velocity (U_0) was 7650, with the operating air jet velocity of 1.16 m/s. A flat glass plate is used as the impingement surface which is rigidly placed and located at a distance H from the nozzle and positioned normally to the jet axis.

In order to avoid structural vibrations from loud speaker, it is mounted at a distance about 4 cm above the jet cylinder in which it is in line with the cylinder axis. The empty space between the loud speaker and cylinder is sealed by rubber. It is evenly mounted from each side and attached to another independent structure to dampen the structural vibrations. Hot-wire method has been used for speed measurement by the lab-made hot-wire anemometers using a 5 μm Pt wire as the sensing element. Hot-wire is calibrated carefully by a high-precision transducer and pitot-tube measurements according to the King's law. For data acquisition, a 16-bit analog to digital converter with data sampling ability is used and connected to a personal computer. The probe was located at the center of the jet and immediately after the jet exit.

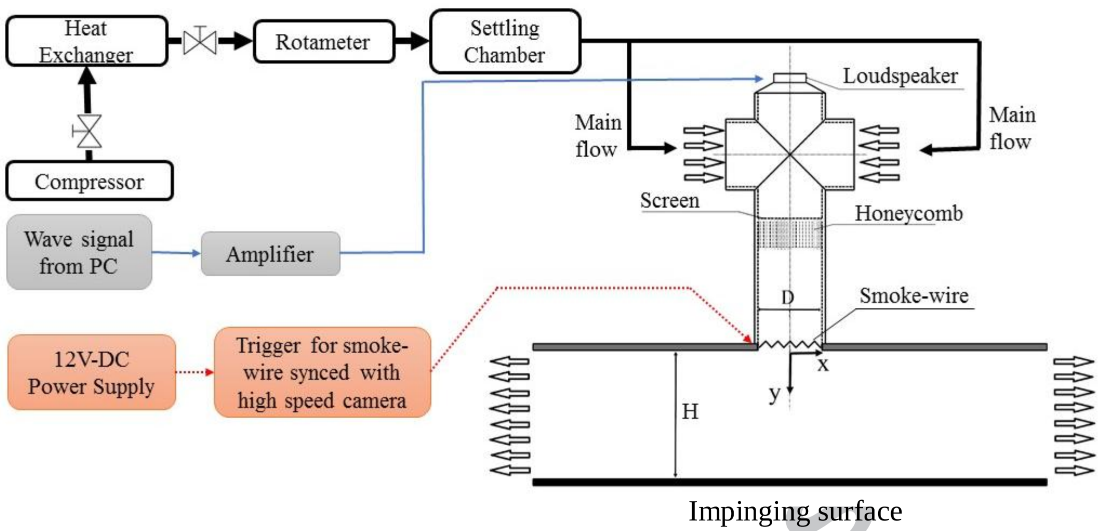

Figure1: schematic diagram of experimental setup and divices

For flow visualization, smoke-wire technique is employed. In order to make the most acceptable and detectable smoke in the stream, engine oil with an adjustable power supply for electric element is considered. Stainless steel wire with a thickness of 0.15 mm is used as smoke-wire which causes the engine oil to evaporate. All photos are taken by a high speed Exilim Casio camera with the filming rate of 120, 240, and 420 frames per second. Two 1000 watt halogen lamps were used as the light source on both sides because of high-speed filming and ensuring that no flickering in frames will occur. Finally, the vortical structures are extracted from snap-shots of a pulsation period.

3. RESULTS AND DISCUSSION

In figures2, the flow field of a steady impinging jet on a flat surface in different aspect ratios (H/D=2, 3) is presented. In general, the flow field in impinging jets can be divided into three main zones which are free jet, stagnation, and wall jet zone. Besides, the free jet region itself categorized into three sub zones which are called potential core, transition, and fully developed. In steady impinging jets, by decreasing the H/D, the instabilities are not going to be allowed to grow and make any larger vortical structures, or in other words, they have no chance to shape cohesive structures and have no choice but to hit the flat plate by potential core. This phenomenon is shown in figure 2. According to this figure, the streak lines are straighter and have less distortion at low value of H/D. Generally, vortical structures in shearing layer are formed near the end of the potential core. As presented in figure 2, vortex structures are clearly formed for H/D=3.

(a) (b)

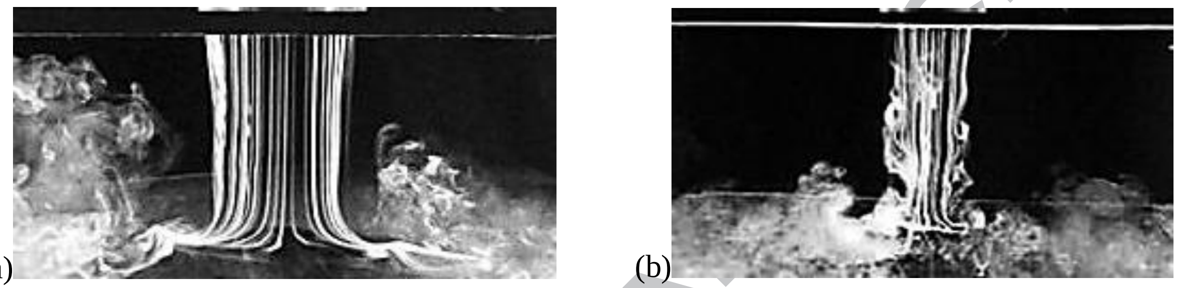

Figure2: Flow visualization of steady impinging jet, Re=7650, a) H/D=2, b) H/D=3

3.1. EFFECT OF FLOW PULSATION ON FORMATION OF VORTICAL STRUCTURES

In this section, the effect of pulsating flow on formation of vortical structures has been investigated. In order to excite the shearing layer, two different types of functions e.g. sinusoidal and step, were applied at the exit of the jet as defined below:

$$u(t) = u_0(1 + A\sin(2\pi f t)) \tag{1}$$

$$\begin{cases} u_{on} = u_0(1 + A/100) \;\; for: \dfrac{n}{f} \langle t \langle \dfrac{(n+1/2)}{f} \\ u_{of} = u_0(1 - A/100) \;\; for: \dfrac{(n+1/2)}{f} \langle t \langle \dfrac{(n+1)}{f} \end{cases} \tag{2}$$

Effects of four frequencies, 1.5, 3, 6, and 9 Hz which correspond to Strouhal numbers of the 0.125, 0.25, 0.5, and 1 were investigated. Figures 3, 4, and 5, present how the frequency of the sinusoidal pulsation signal affects the vortical structures. By comparing the steady jet with the pulsating one according to figure 2 and 3, it is observed that the vortical structures are greatly influenced by external excitation. Actually, these structures also exist in steady jets but they are not large enough to be detected easily. External pulsation causes vortical structures to be formed with more regularity and period at the end of the potential core. Vortices become larger when they move downstream and finally dissipate in the wall jet region. These results are in agreement with Katoaka et.al. [21] and Yul et. al. [26] which were reported that vortices which are formed in the shearing layer dissipate after specific distance by breaking into smaller eddies and eventual dissipation of turbulence kinetic energy. By comparing snapshots taken at different times within a single period, it was observed that the flow experiences a periodic pattern at the frequency of excitation.

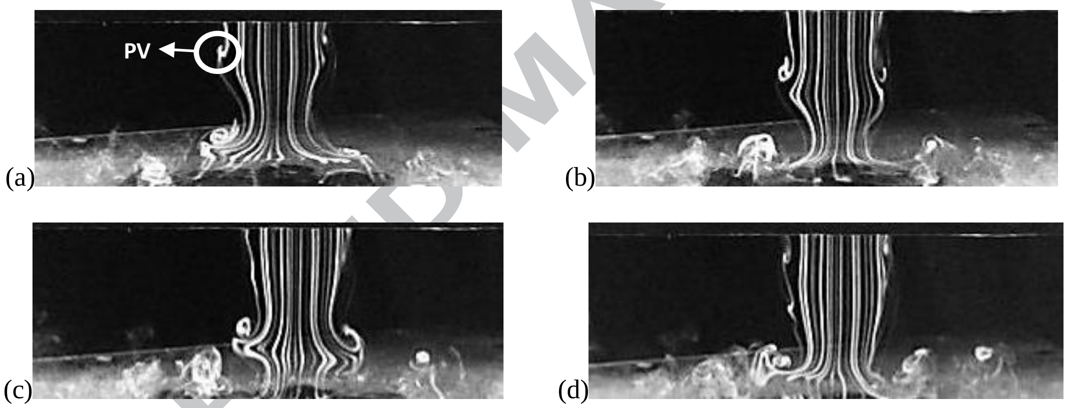

Figure 3: Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=1.5, A=20%,) T/4, b) T/2 c) 3T/4 d) T

The frequency of pulsating flow has a great influence on the quality, size, and dynamics of the vortex. At higher frequency, the potential core length decreases and jet expands more rapidly. This phenomenon causes the primary vortices (PV) to be formed at shorter distances and as a result, they have better chance to develop and interact with others at higher frequencies. Primary vortex is defined as vortices that roll-up in the shear layer near the nozzle leap and convect toward the impingement surface and interact with it. As a result of this interaction, a secondary vortex (SV) forms between the primary vortex and the impingement surface. At the frequency of 1.5 Hz, just one vortex is formed at about y/D=0.3 and it makes larger as it moves downstream until it hits the wall. But at 3 Hz (Figure4), after forming the first vortex, the second vortex will be formed immediately after the first one within short distance. These two vortical structures merge near the impingement surface and form larger vortex. Also the vena contracta phenomenon occurs between the two vortices that causes contraction of the stream and accelerates the flow before hitting the wall. These vortical structures play an important role in transport phenomena. Generally, this phenomenon means the vortices which are formed in the shearing layer can replace the fluid near the wall with fluid in the environment. Thus, the number of vortices, their strength and size play key role in affecting wall heat transfer. Vortical structure formation at 6 Hz is different from the 1.5 and 3 Hz cases as shown in figure 5. In this case, three vortices are formed at different distances from the nozzle exit. These three vortices do not merge together and even remain in good order in the wall jet region and dissipate eventually. It can be anticipated that some points with relative local maxima will be observed due to the existence of vortices with different powers. So, it is expected if the heat transfer is considered in this frequency, the local Nusselt distribution on the impingement surface will have three maxima at different distances. The other noticeable aspect of the excitation frequency of 6 Hz is the size of the vortices, which are larger than those at 1.5 and 3 Hz. The vena contracta phenomenon is much more significant as well.

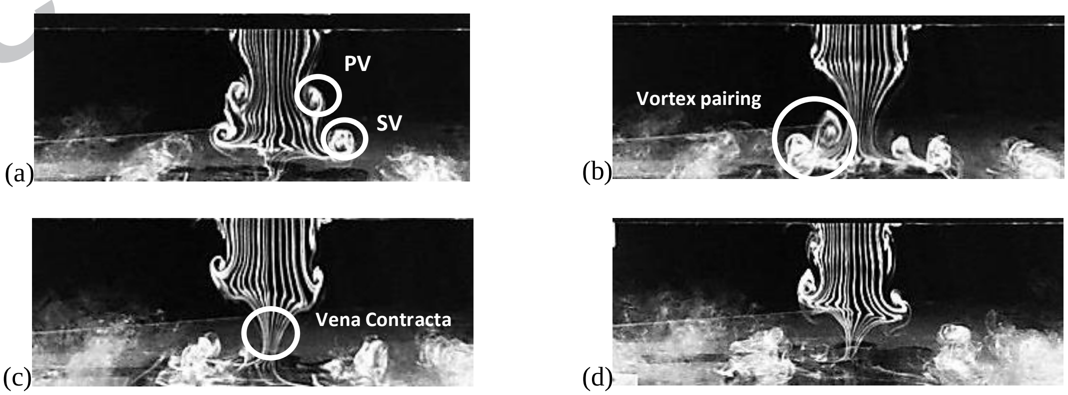

Figure 4: Formation and development of primary (PV) and secondary vortex (SV) at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=3, A=20%, a) T/4, b) T/2, c) 3T/4, d) T

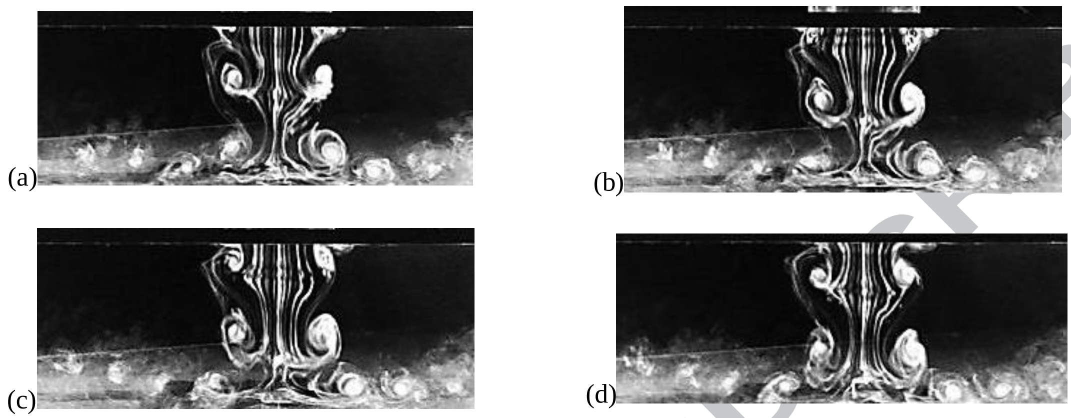

Figure 5: Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=6, A=20%, a) T/4, b) T/2, c) 3T/4, d) T

Flow characteristics of the pulsed impinging jet at a frequency of 9 Hz are shown in figure 6. Relative to the vortex size for 6 Hz, the vortex is smaller at 9 Hz. It seems that there is a critical frequency after which the vortices' size becomes smaller. According to this fact that Strouhal number is defined as the ratio of two time scales, which are flow time scale to pulsation time scale (1/f), the time of a full period will increase with enhancing the frequency of excitation. Thus, the flow behavior of the pulsating impinging jet will go toward the behavior of a steady impinging jet in which the effects of external excitation is too weak to be detected. Due to this fact, vortices at higher frequencies are weaker and dissipate more rapidly over shorter distances. This phenomenon can be observed by comparing vortical structures in figure 4, 5, and 6. So, it can be concluded that there is a critical value of Strouhal number in which the external excitation have the greatest impact on vortical structures.

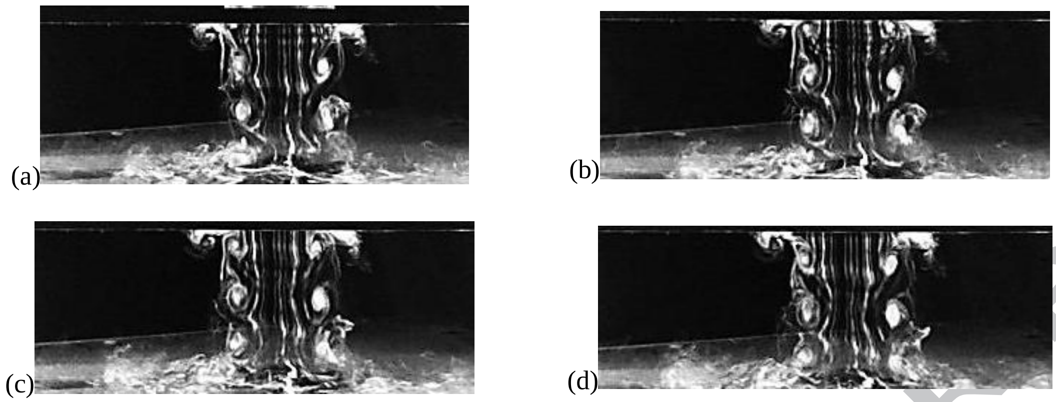

Figure 6: Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal H/D=2, Re=7650, f=9, A=20%,) T/4, b) T/2 c) 3T/4 d) T

3.2. EFFECT OF PULSATION SIGNAL SHAPE ON FORMATION OF VORTICAL STRUCTURES

In order to investigate the effect of pulsation signal shape on the formation of vortical structure, the inlet jet was excited acoustically with a step function and the flow visualization results are presented for a complete period of pulsation in figures 7 and 8. According to the snapshots, the formation, size, and behavior of the vortical structures due to the step function is completely different from those for the sinusoidal ones. In the step type of excitation, the stream experiences two sudden changes in momentum for every period which causes a pulsatile behavior in the flow. By comparing every snapshot of sinusoidal and step function, it is observed that sudden changes of inlet mass flow rate create much larger structures. For instance, it is observed that two vortices that formed in the shear layer of the step signal merge with each other for the frequency of 1.5 Hz, which is not observed in the same frequency for sinusoidal type. Thus, due to the fact that larger vortical structures formed as a result of Step type of excitation, the ratio of expanded to contracted part of jet’s main flow is more apparent than in the sinusoidal one, and it is expected that the transport phenomena occur at higher rate. Many researchers have investigated the rate of heat transfer in pulsating impinging jets with step type of excitation are more than one excited with sinusoidal type. The also claimed that increasing the amplitude and frequency of pulsation intensifies the rate of transport phenomena. By decreasing the frequency, vortices that develop in the shearing layer merge with each other near the stagnation region. Vortex merging is observed at the frequencies of 1.5 and 3 Hz but not for 6 and 9 Hz. Because by enhancing the frequency, the vortices are more autonomous and organized in line. This event is clearly visible at the frequency of 9 Hz.

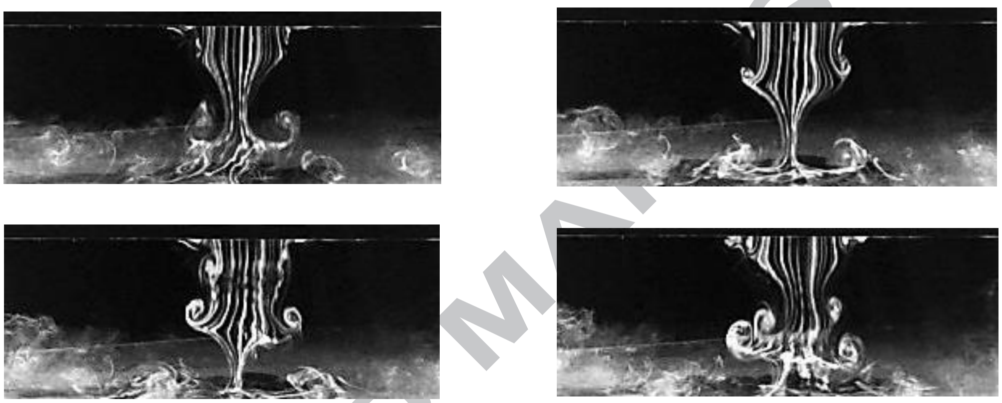

Figure 7: Visualization of pulsed impinging jet flow at different times in the period, step signal H/D=2, Re=7650, f=1.5, A=20%,) T/4, b) T/2 c) 3T/4 d) T

The signal shape of pulsation has significant impact on the convection velocity of the vortex core. Due to the fact that overall mas flow rate of fluid stays as minimum speed for half of the period in the step type of excitation, it serves more time for the flow kinetic energy to be dissipated and also expanded radially. Thus, the convection velocity of the vortex core in the step type of pulsation is less than the sinusoidal one. But on the other hand, results of flow visualization show that step type of excitation make larger vortical structures than sinusoidal one. Thus, vortices with sinusoidal excitation reach their destination toward the impingement surface sooner than they do in the step case in one period.

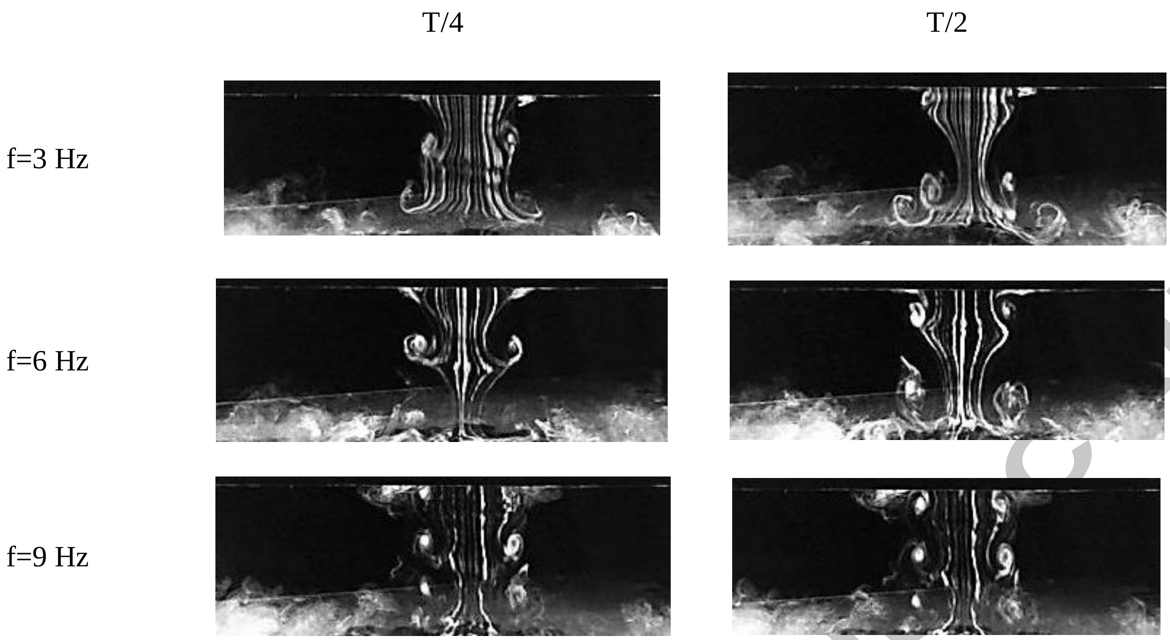

Figure 8: Visualization of pulsed impinging jet flow at two typical times in the period (T/4, 3T/4) and various frequencies, step signal, H/D=2, Re=7650, A=20%

The Dynamics of vortical structures in pulsed impinging jet has a crucial role in transport phenomena. For a better understanding of the flow dynamics, two characteristics of vortex structures include transverse distance (B_w) and instant distance of vortex core from nozzle exit (L_h) are extracted from the experimental data. The flow patterns which are formed by acoustical excitation of the jet flow are presented in figure 9. The locations where smoke particles are concentrated are recognized as the location of the vortices core. So, the precise location of the vortices core in any snap-shots is extracted by meshing the flow field.

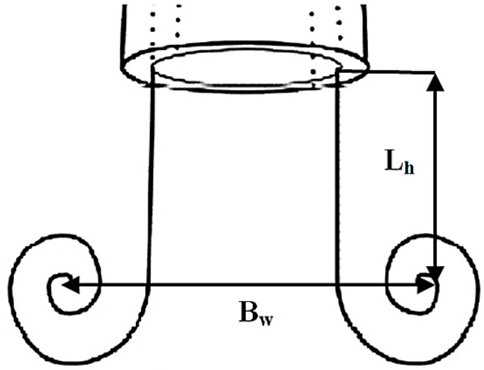

Figure 9: Flow pattern model in pulsed impinging jet

Variation of the vortex core location (L_h/D) with time at various frequencies for step and sinusoidal signals is shown in figures 10 and 11. In fact, the slope of this diagram shows convection velocity of the vortices core toward impingement surface. As expected, the slope is different in each region of flow field due to this fact that as vortices arrive closer to the wall, their velocities are reduced. The increase of pulsation frequency increases the vortex core convectional velocity. The main reason for this observation is the formation pattern and size of vortical structure and interactions between them at different frequencies. This fact can be justified by this analysis that larger structures have greater inertia. On the other hand, by considering the type of excitation function it can be observed that vortices move faster in the sinusoidal pulsating jet than in the step one. The size of vortices in the step case is larger than in the sinusoidal but their movement velocity varies inversely because of inertial effects of larger vortices.

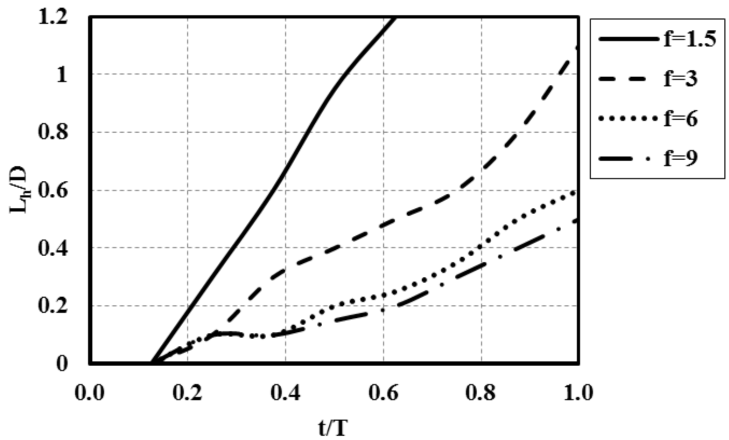

Figure 10: Variation of L_h/D with time for various frequencies, Sinusoidal signal, H/D=2, Re=7650, A=20%

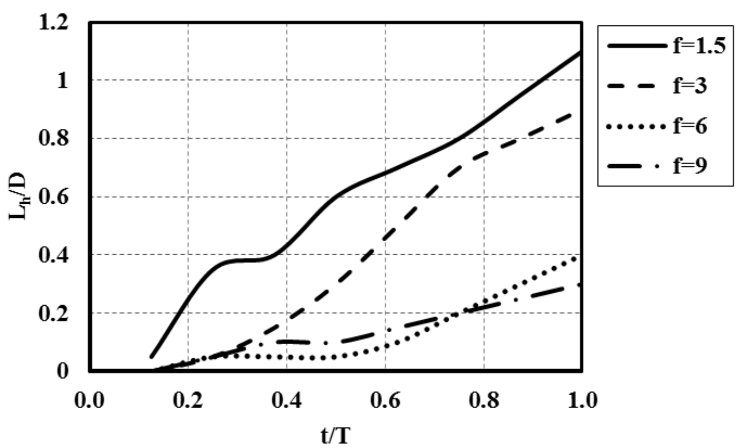

Figure 11: Variation of L_h/D with time for various frequencies, Step signal, H/D=2, Re=7650, A=20%

Mixing is an important characteristic of jets in industrial applications. Since the mixing phenomenon is influenced by the vortical structures evolving in jets shear layer, it is significant to consider the vortical structures related to the mixing process. In circular impinging jets, axisymmetric and streamwise vortical structures interact with each other and stagnant surrounding fluid and finally break down. According to the type of pulsation signal shape and frequency, the rate of jet expansion or mixing with the surrounding fluid is different. As shown in figure 12, 13, when the frequency increases, more vortical structures form in the shearing layer. But, these vortices behave independently and consequently put each other in the straight line pattern. Thus, by increasing the frequency in pulsating jets, rate of mixing in surrounding fluid decreases.

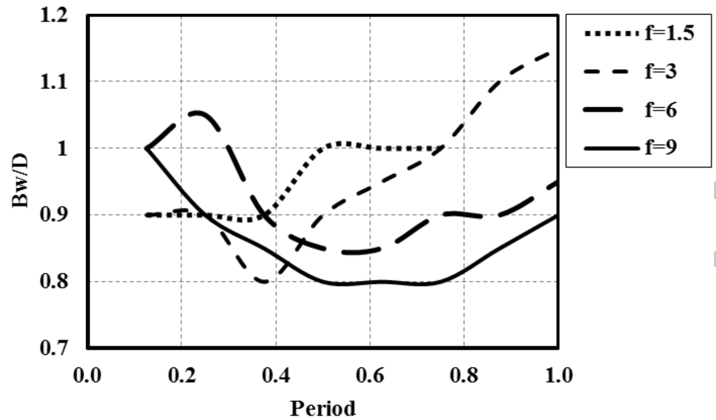

Figure 12: Variation of B_W/D with time for various frequencies, Sinusoidal signal, H/D=3, Re=7650, A=20%

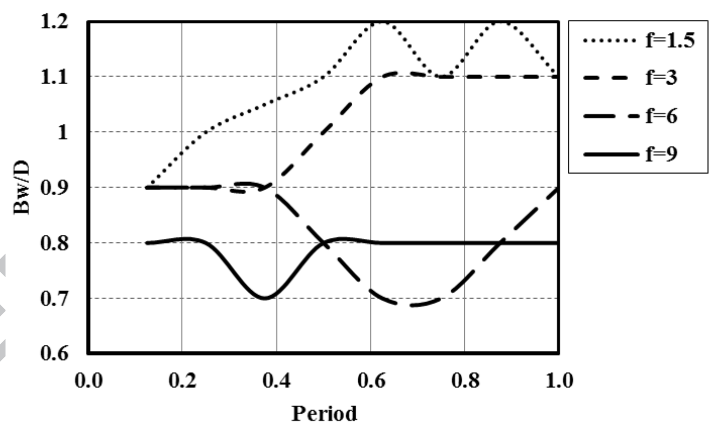

Figure 13: Variation of B_W/D with time for various frequencies, Step signal, H/D=3, Re=7650, A=20%

4. CONCLUSION

In this study, pulsation the mass flow rate of jet has been employed as an active control method to control the vortical structures formed by a turbulent impinging jet. Results of this investigation show that the flow pattern and size of the vortical structures in pulsating impinging jets are very different from those for a steady one. Flow pulsation leads to periodic formation of vortical structures. In addition, this study provides some useful techniques to control or excite the dynamical behaviors of turbulent impinging jets, which can enhance the transport phenomena. The vena contracta phenomenon in the step mode of pulsating impinging jet is more apparent due to the formation of larger vortical structures. By increasing the frequency, the vortices will be more autonomous and are placed in line. Therefore vortex merging is observed at the frequencies of 1.5 and 3 Hz but not for 6 and 9 Hz. By increasing the frequency of the pulsating impinging jets, it is observed that mixing rate in surrounding fluid decreases.

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Fig. 1 schematic diagram of experimental setup and divices.

Fig. 2 Flow visualization of steady impinging jet, Re=7650, a) H/D=2, b) H/D=3

Fig. 3 Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=1.5, A=20%,) T/4, b) T/2 c) 3T/4 d) T

Fig. 4 Formation and development of primary (PV) and secondary vortex (SV) at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=3, A=20%, a) T/4, b) T/2, c) 3T/4, d)

Fig. 5 Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal, H/D=2, Re=7650, f=6, A=20%, a) T/4, b) T/2, c) 3T/4, d) T

Fig. 6 Visualization of pulsed impinging jet flow at different times in the period, sinusoidal signal H/D=2, Re=7650, f=6, A=20%,) T/4, b) T/2 c) 3T/4 d) T

Fig. 7 Visualization of pulsed impinging jet flow at different times in the period, step signal H/D=2, Re=7650, f=1.5, A=20%,) T/4, b) T/2 c) 3T/4 d) T

Fig. 8 Visualization of pulsed impinging jet flow at two typical times in the period (T/4, 3T/4) and various frequencies, step signal, H/D=2, Re=7650, A=20%

Fig. 9 Flow pattern model in pulsed impinging jet

Fig. 10 Variation of L_h/D with time for various frequencies, Sinusoidal signal, H/D=2, Re=7650, A=20%

Fig. 11 Variation of L_h/D with time for various frequencies, Step signal, H/D=2, Re=7650, A=20%

Fig. 12 Variation of B_W/D with time for various frequencies, Sinusoidal signal, H/D=3, Re=7650, A=20%

Fig. 13 Variation of B_W/D with time for various frequencies, Step signal, H/D=3, Re=7650, A=20%

Highlights

- **The effects of flow pulsation on formation of coherent structures are investigated in turbulent confined impinging jet.**
- **The effects of key parameters such as pulsation frequency and signal shape on behavior of vortex structures studied.**
- **Significant differences in flow pattern and size of the vortical structures between pulsed and steady jet are observed.**
- **The increase of frequency, make the vortices more autonomous and organized.**
- **The size of vortical structures in step type of excitation is larger than those in sinusoidal one.**