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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.

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

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Nomenclature

A	amplitude of Pulsation (dimensionless $= \frac{U_{max}-U_0}{U_0} \times 100$)	St	Strouhal number ($= \frac{fD}{U_0}$)
B_w	transvers distance between vortex cores (m)	T	pulsation period (s)
D	nozzle Diameter (m)	T	time (s)
f	Pulsation frequency (Hz)	$U(t)$	instant jet velocity at inlet , (m s^{-1})
H	nozzle-to-surface spacing [m]	U_0	average air velocity at inlet (m s^{-1})
L	longitude of nozzle cylinder (m)	U_{max}	maximum velocity (m s^{-1})
L_h	instant distance of vortex core from nozzle exit (m)	x, y	coordinates (m)
Re	Reynolds number ($= \frac{\rho U_0 D}{\mu}$)		

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 $1200 < Re < 120{,}000$, $10^{-4} < St < 10^{-2}$, 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. Iio 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' spanwise 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 Fig. 1. A 2-cylinder compressor which can provide 248 l air per minute, connected to a 250 l high-pressure tank is the air source for the experiment. The air passes through a water–air heat