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Mixing and entrainment characteristics of a pulse jet

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Pulsating jets can be more useful for enhancing mixing and heat transfer than steady jets; however, their flow physics is still not clear. In this work, particle image velocimetry based measurements have been undertaken to investigate the flow structure and mixing characteristics of axisymmetric pulsating jets. This experimental study deals with flow characterization of 20 mm diameter of axisymmetric submerged water jet over a wide range of test parameters. The purpose of this study is to understand the influence of frequency and amplitude on the flow characteristics, and the characteristics of turbulent/non turbulent (T/NT) interface of a pulsating jet. The flow characteristics across the T/NT interface has been compared for potential core, transition zone and fully developed zone. The introduction of pulsation results in widening of the jet and shortening of the potential core length as compared to steady jets. It is also observed that shear layer in pulsating jet oscillates with lower frequency as compared to the jet frequency, while the amplitude depends on the location in the flow field. Further, entrainment and mixing of surrounding fluid increases up to an optimal frequency. These results should eventually lead to a better understanding of the physical phenomena responsible for enhanced mixing and heat transfer in pulsating jets.

1. Introduction

Significant attention has been paid to free jet due to its widespread application in the process of mixing, drying and combustion phenomena. In reciprocating combustion engines, spreading and entrainment rate of the jet are the controlling factors for efficient burning of the fuel. A better understanding of spreading and mixing of jet can therefore help in enhancing the thermal efficiency of the engine and reduce the emission of pollutants. Spreading and mixing of the jet can be further improved with pulsed jet, due to the pulsatile nature of the flow. Mixing and entrainment characteristics of steady jet have received considerable attention both theoretically and experimentally (Ricou and Spalding 1961; Paizis and Schwarz 1975; Rankin et al. 1983; Dahm and Dimotakis 1987; Popiel and Trass, 1991). The flow characteristics of pulsed jets, including effect of pulsation and amplitude on the jet, have however been seldom reported in the literature; hence the flow characteristics are not completely understood. To partially overcome this shortcoming, we employ the particle image velocimetry (PIV) technique here for studying the fluid flow, formation and development of vortices, and characteristics of turbulent/non-turbulent (T/NT) interface in pulse jets.

Farrington and Claunch (1994) investigated the influence of flow pulsation of a planar air jet on its flow structure with the help of infrared imaging and smoke-wire visualization. They observed that the highest mixing occurs at $St = 0.168$ for $Re = 7200$. For $0 < St < 0.324$, the structure in the unpulsed jet was smaller and less ordered as compared to pulsed jet. The flow characteristics of circular jet with/without acoustic excitation was investigated with the help of spectral analysis of instantaneous velocity field and flow visualization (through the Schlieren technique) by Han and Goldstein (2007). Johari and Paduano (1997) visualized the pulse jet flow structure in gravity driven flow created by using a solenoid valve using florescent dye. By using acid base neutralization reaction, they observed that a pulse jet mixes in a shorter distance as compared to a steady jet. However, this study did not reveal any dependency of pulse jet on the pulsing frequency. Grosshans et al. (2014) visualized the mixing characteristics of a pulse jet in a combustion chamber. They concluded that the pulse jet enhances the mixing phenomenon as compared to a steady jet. The injection frequency showed a small effect on mixing in the spray region but did not affect mixing in the atomization region. During the first few injection pulses, considerable enhancement in the mixing process was observed with an increase in the injection frequency. A solenoid valve was used by Otani et al. (1995) to produce a pulse jet in order to develop an effective dry surface. Their results showed that a pulse air jet was highly effective in drying and cleaning processes. The heat transfer characteristics

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of pulse jet have been also studied by several researchers (Sheriff and Zumbrunnen 1994; Behera et al. 2007; Nevins and Ball 1961; Eibeck et al. 1993; Camci and Herr 2002; Hofmann et al. 2007a,b; Zulkifli and Sopian 2007; Azevedo et al. 1994).

Many shear flows such as mixing layer, jet and wake exhibit a sharp interface in which one fluid is characterized by rotational flow (turbulent flow) while the other fluid is essentially irrotational. It is important to mark this interface separating rotational / irrotational fluids. Several important process such as exchange of properties (such as mass, momentum and energy) occurs across this interface. Corrsin and Kistler (1955) called this as the T/NT interface. They reported that the thickness of this super layer is of the order of Kolmogorov length. During the entrainment process, fluid elements from the irrotational flow region interact through diffusion process with the highly turbulent fluid region, acquire vorticity, and become part of the rotational/turbulent region (Corrsin and Kistler, 1955). In this way, the spreading of a jet occurs while keeping its momentum constant; the increase in jet width is appropriately compensated by a reduction in the average velocity of the jet. Townsend (1966) suggested that the entrainment process is caused by large-scale eddy motions across the T/NT interface. This view was held by the community for a long time. In contrast, Da Silva et al. (2014) performed direct numerical simulation for a turbulent plane jet at Re = 120. They observed, by computing the invariants of the strain rate tensor, that the entrainment process is mainly due to nibbling by the small eddies across the interface. The earlier studies of Mathew and Basu (2002) and Agrawal and Prasad (2004) have also suggested that entrainment occurs across T/NT interface through small scales.

Our literature survey shows that although there are a few studies on heat transfer with pulse jet, the flow characteristics of pulse jet is not well documented and understood. Further, mostly qualitative techniques (such as smoke wire based visualisation, Schlieren technique, florescent dye, etc) have been employed in the past, making them limited in their scope. Previous studies assumed that impinging jet characteristics is same as the free jet characteristics, due to paucity of flow data. This shows that the understanding of the flow characteristics of pulse jet is limited, which provided the motivation for undertaking the current work. In the present work, the PIV technique is employed to investigate the velocity field and the associated flow structures. This study will help to understand the influence of frequency and amplitude on the flow characteristics of pulse jet, which will eventually help to choose the optimal value of these parameters. The present study also examines the characteristics of turbulent/non turbulent (T/NT) interface of a pulse jet.

2. Experimental apparatus and data collection

The measurements are carried out in a rectangular tank made of 1.3 cm thick acrylic sheet, with inner dimensions of $70 \times 38 \times 40\ cm^3$ (Yadav et al. 2015). Schematic diagram and photographic view of the experimental setup is shown in Fig. 1. The overall arrangement of the experimental setup comprises a water storage tank, settling chamber, two pumps, test tank, solenoid valve, pressure gauge, pulse driver, manometers and venturi meters. The issuing fluid from the jet and the surrounding fluid in the test section are both water, maintained at constant temperature. A constant height of 38 cm is maintained in the test tank by partitioning the tank and pumping water with the help of a centrifugal pump. The partition in the tank and settling chamber helps avoid any disturbance from the pump to the flow. A pressure gauge is mounted on the settling tank to ensure that constant pressure is maintained during the experiments. A pre-calibrated venturi meter placed ahead of the settling tank records the flow rate. A solenoid valve based pulse driver is used to induce pulsations in the flow. The pulsating flow passes through a venturi meter positioned prior to the test tank. Another venturi meter records the flow rate of the pulsating flow. A pressure sensor (GE, UNIK 5000) connected with venturi meter before to solenoid valve gives the total flow rate. As the flow is divided in to two parts, some flow goes through the test section while the rest of the flow is discharged through the solenoid valve. The flow passing through the test sections is measured by another (magnetic) flow meter (Rosemount, China). The pulsating flow is introduced in the test tank as a jet. A constant water level is maintained in the test tank by a re-circulating pump, which sucks water back in to the storage tank. The amplitude of the pulsating flow has been varied with the help of solenoid valves having different orifice diameters.

The experimental setup employed here is customized for PIV measurements. Water seeded with tracer particles (spherical hollow glass particles with mean size of 8–11 μm) made of fused borosilicate glass (density 1.1 $g\,cm^{-3}$) is pumped into the test tank. The jet is illuminated using twin Nd:YAG pulsed lasers (Vlite-700, Beamtech, China). The wavelength of laser beam is 532 nm and the maximum output energy of the laser beams is 200 mJ/pulse. The duration of the two pulses is 7.7 and 6.8 ns (Sewatkar et al. 2012; Yadav et al. 2015; Hashiehbaf et al. 2015). A laser sheet is created using a combination of spherical and cylindrical lenses. The light sheet is projected on to the test section. The illuminated flow region with tracer particles is recorded using a 1024×1392 pixels 12-bit CCD (Pixelfly, PCO, Germany). The seeded tracer particles in water scatter light, which is captured by the CCD. The laser and CCD are synchronized with a synchronizer that provides appropriate timing for triggering them. The synchronizer unit is controlled by a computer from where parameters such as pulse frequency and time delay between the laser pulses are controlled. By calculating the particle displacement in an interrogation spot over the time delay, the local velocity can be determined within the imaging region.

In general, four factors which are primarily responsible for uncertainty with PIV measurements have been considered in the uncertainty analysis. These factors are: uncertainty related to equipment, uncertainty in particle lag, sampling, and image processing (Lazar et al. 2010; Raffel et al. 1998; Wang et al. 2007; Coleman and Steele 2009). The individual uncertainty in each of these factors was estimated as given in these references. These uncertainties were combined using the standard uncertainty propagation method. The combined experimental uncertainty is about ± 1.22%, ± 1.4%, ± 1.65% of the mean velocity in developing, transition and fully developed zone respectively.

The Reynolds ($Re = \frac{U_{avg} D}{\nu}$) is calculated based on nozzle diameter (D), where U_{avg} is the cross-section averaged velocity (ratio of the average flow rate at the nozzle exit (Q_{avg}) to the cross-sectional area of nozzle, A_{nozzle}). The time averaged mean velocity {U_m (X, r)} data is calculated as a function of position (X, r) in the flow field from PIV data for 152 pair of images, for each Reynolds number case (both steady as well as pulsating jet). Here, X is the streamwise coordinate and r is the radial coordinate. The turbulence intensity (TI) is determined as ratio of the root mean square velocity (U_{rms}) to the time averaged velocity (U_m). The amplitude of pulsation (A) is determined for pulse jet as the ratio of difference of maximum flow rate (Q_{max}) to average flow rate to the average flow rate. Note that Q_{max} is the maximum flow rate in to the test section (during the OFF time of the solenoid valve). The frequency of the solenoid valve is set by a pulse driver (Iota One Pulse Driver, Parker). The generated pulse trains can be achieved by setting ON and OFF times or specifying an operating frequency.

The pulse frequency values are chosen (after sufficient trials) such that they substantially affect the jet behavior. Further, a sufficiently large range is chosen to show the presence of an optimal frequency. The measurements are performed at three different