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Structure of a Zero-net-mass-flux round jet in crossflow

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Abstract

Planar laser induced fluorescence (PLIF) has been used to investigate the mean structure of circular Zero-Net-Mass-Flux Jet in Crossflow (ZNMF-JICF). The flow structure of these jets is primarily characterized by the Reynolds number (Re), the Strouhal number (St) and the velocity ratio (VR). The prime focus of this study is to investigate the effect of different VR and St numbers on the mean structure of the ZNMF-JICF. The Reynolds number for all the ZNMF-JICF experiments was kept constant at 1066. Four velocity ratios, VR = 2,3,4 and 5 were used in the investigation of the ZNMF-JICF. For each VR, the ZNMF-JICF experiments were carried out for Strouhal numbers ranging from 0.08 to 0.56. PLIF experiments revealed that there is a critical Strouhal number in the range between 0.11 to 0.19 that separates the mean structure of the ZNMF-JICF into a single trajectory ZNMF-JICF for $St < 0.11$ and a multiple trajectory ZNMF-JICF for $St \geq 0.19$.

Introduction

The flow of turbulent jets in crossflow is encountered in a variety of applications including pollutant discharges, STOVL (Short Take off Vertical Landing), combustion processes, film cooling of turbine blades and missile control systems. Even though extensive research has gone in the investigation of jets in crossflow many aspects of the flow remain unexplored. The primary reason being that these flows are difficult to predict accurately due to the inherent complexity of the jet-crossflow interaction.

The majority of the studies reported in the 1970's and 1980's were motivated by VSTOL-related applications and several flow visualization and experimental studies were conducted to understand the characteristics of the jet-crossflow interactions.

This study reports the measurements of a zero-net-mass-flux jet in crossflow (ZNMF-JICF). A zero-net-mass-flux jet is a mechanically excited fluid stream formed by no addition of external fluid to the system during the generation of the jet. These jets have non-zero mean streamwise momentum formed by the interaction of vortices. The vortices are generated by the periodic oscillation of a fluid boundary and propagate due to the non-linear term in the governing equations of motion. [2] found that the spreading rate of a round turbulent ZNMF jet is greater than an equivalent continuos jet throughout the measured domain. Previous research based on continuous, pulsed or ZNMF jets suggest that a presence of cross flow enhances the mixing of the jet as compared to a free jet. Pulsing the flow further improves the mixing of the jet [9,10]. Investigation reported by [8] revealed that a fully modulated jet always penetrates more than the corresponding steady jet at the same time-averaged velocity. Recent studies of ZNMF jets show that they have a higher entrainment rate compared to their continuous counterparts [2,11]. The present study investigates the observed characteristics of single and multiple-trajectory ZNMF jets created using a piston-cylinder assembly coupled with a scotch-yoke mechanism.

Experimental Setup

The experimental investigation was carried out in a square 250 mm closed-circuit vertical water tunnel at the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC) at Monash University, Melbourne, Australia. The tunnel has a 1.5 m long working section made of 15mm thick Perspex. Water is introduced into the settling chamber using a spray system at the head of the tunnel, which is then passed through a perforated plate, four stainless steel wire screens, a honeycomb and a 16:1 contraction before entering the working section of the water tunnel. The contraction provides smooth, uniform flow in the working section of the tunnel with the freestream turbulence intensity of less than 1% [1]. Sinusoidal oscillation of a 20 mm diameter piston (D_p) in a cylindrical bore through a 10mm diameter orifice (D_o) generated the ZNMF-JICF. The piston-cylinder apparatus was mounted on a horizontal rail and attached the water tunnel wall. This setup is shown in Figure 1. The piston is connected via a coupling to a scotch-yoke mechanism, which is driven by a PC controlled stepper motor. The ZNMF apparatus was specifically constructed to achieve low excitation frequencies ranging from 0.5 – 6 Hz. The displacement history of the piston was recorded by a LVDT axially aligned with the piston-cylinder setup. The static pressure of the water column in the tunnel did not have an effect on the motion of the piston [3].

The water tunnel flow was seeded with 11 μm diameter hollow glass spheres with a density of 1100 kg/m^3 prior to the PIV experiments. The ratio of the relaxation time for the particles to the excitation frequency of 5Hz was in the order of 10E-6 and even smaller for lower excitation frequencies. This suggests that the particles will follow the fluid motion in the tunnel with high fidelity. These particles were illuminated using a 2 mm thick pulsed laser light sheet produced with an appropriate cylindrical/spherical lens arrangement and a Quanta System dual cavity Nd: YAG laser. It is capable of producing 6-ns, 200-mJ pulses at a repetition rate of 15Hz

The mean jet velocity (U_j) was 106.6mm/s for all the experiments and the velocity ratio was adjusted by changing the velocity of the freestream fluid (U_∞). The jet velocity was kept the same to allow exactly the same flowrate of dye through the orifice.

The single exposed images of the seed particles were acquired with a 12 bit 1.3 Mega Pixel (1280 x 1024) PCO Pixelfly CCD camera. The camera was mounted on a bevel-geared vertical railing system and the position was measured using a set of rulers positioned in the x, y and z-axes. A micrometer installed in the z direction controlled the minute motion of the camera in that direction. An optical sensor monitoring the stepper motor was used to trigger the laser.
The entire image acquisition system was controlled using an in-house developed Real-time Linux (RTAI) computer program.

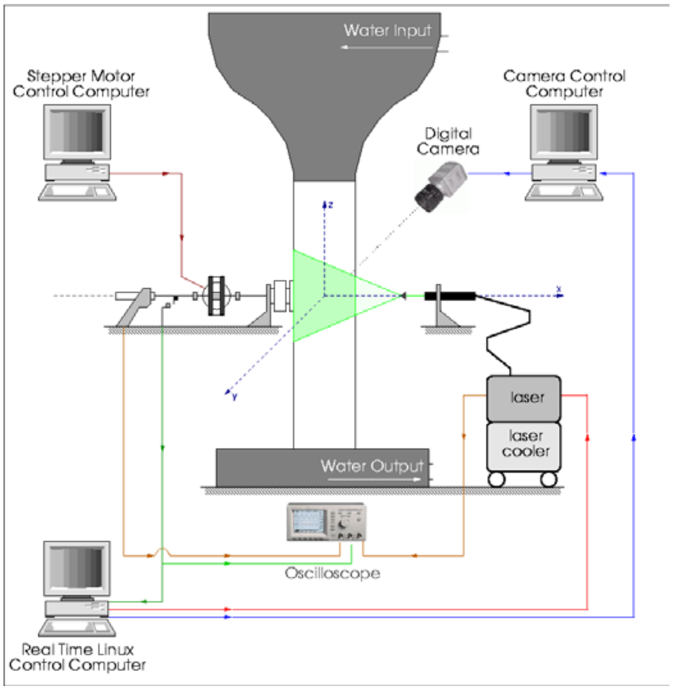


Fig 1. Vertical Water Tunnel Setup

The flow was visualized using Kiton Red 620 fluorescent dye, which has a Schmidt number of approximately 5000. Eight dye injection ports are located on the circumference of the cylinder in which the piston oscillates. The Kiton Red dye, driven by a gravity-based system, enters the cylinder via these ports. During the injection of the dye in the cylinder the piston is oscillated at the required frequency (*f*) and amplitude (*a*) to facilitate mixing of the dye in the cylinder. After the cylinder is completely filled with dye, an injection valve is turned off to preserve the zero net mass flux nature of the system. The piston is oscillated for about 30 seconds after the valve has been shut to allow the steady dye flow through the orifice. The co-ordinate axes have been shown in Figure 2 relative to the location of the orifice plate and the tunnel.

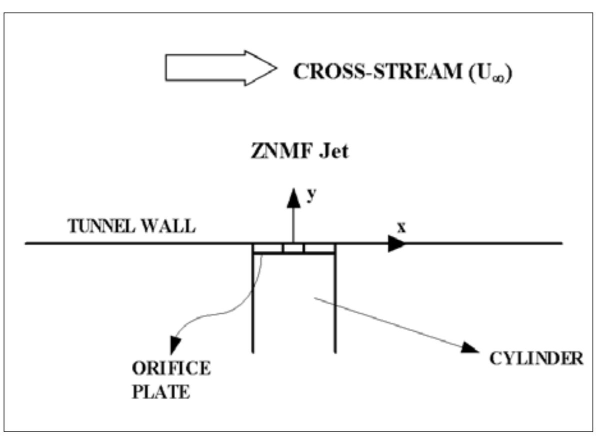


Fig. 2. Schematic of ZNMF-JICF in the test section and coordinate axes the tunnel.

Flow Parameterization

The parameters governing the flow are shown by equations 1-6 .

$$St = \frac{f D_o}{U_j} \; ; \; Re = \frac{U_j D_o}{\nu} \qquad \text{Eq(1)}$$

From [3], the angular velocity (ω) of the piston is given by

$$\omega = 2\pi f \qquad \text{Eq(2)}$$

The maximum velocity of the piston (V_{max}) is given by

$$V_{max} = \omega a = 2\pi f a \qquad \text{Eq(3)}$$

The rms velocity of the piston (V_{rms}) is equal to $V_{max}/\sqrt{2}$.
From [3],

$$V_{rms} D_p = U_j D_o \qquad \text{Eq(4)}$$

Hence,

$$U_j = \frac{\sqrt{2}\pi f a D_p}{D_o} \qquad \text{Eq(5)}$$

Substituting Eq (5) into Eq (1), St and Re are modified as shown in Eq (6),

$$St = \frac{D_o^2}{\sqrt{2}\pi D_p a} \; ; \quad Re = \frac{\sqrt{2}\pi f a D_p}{\nu} \; ; \quad VR = \frac{U_j}{U_\infty} \qquad \text{Eq(6)}$$

The Strouhal number shown by Eq(6) does not depend directly on the frequency of oscillation. The reason is that the product of frequency and amplitude is a constant as shown by Table 1.
The jet velocity, U_j, is a velocity scale chosen based on the mean momentum flow of the jet through the orifice. Table 1 shows the parameters for the twenty ZNMF-JICF.

VR	A (mm)	f (Hz)	St
2	2	6	0.56
2	4	3	0.28
2	6	2	0.19
2	10	1.2	0.11
2	14	0.86	0.08
3	2	6	0.56
3	4	3	0.28
3	6	2	0.19
3	10	1.2	0.11
3	14	0.86	0.08
4	2	6	0.56
4	4	3	0.28
4	6	2	0.19
4	10	1.2	0.11
4	14	0.86	0.08
5	2	6	0.56
5	4	3	0.28
5	6	2	0.19
5	10	1.2	0.11
5	14	0.86	0.08

Table 1. The table of parameters for the ZNMF-JICF.

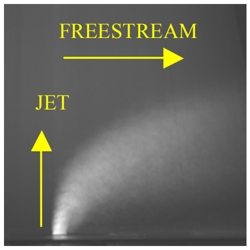
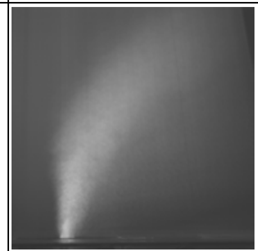
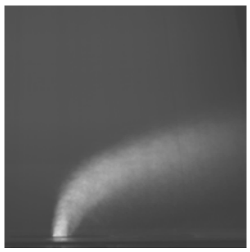
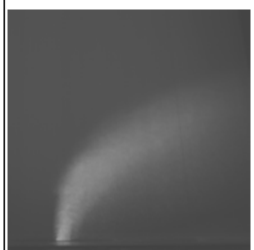
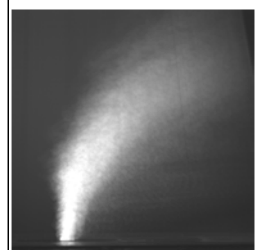
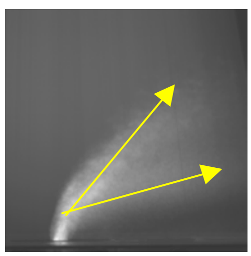
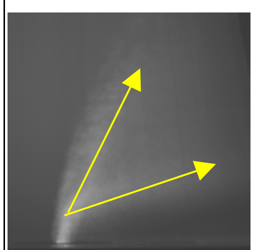
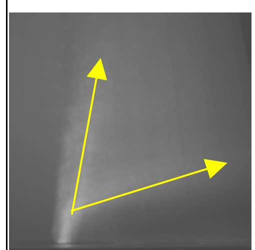
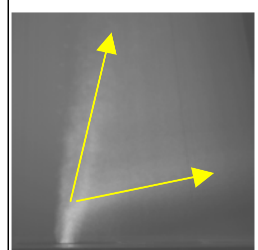
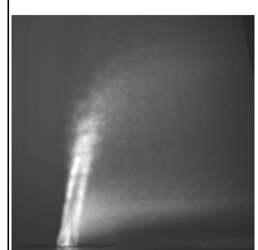
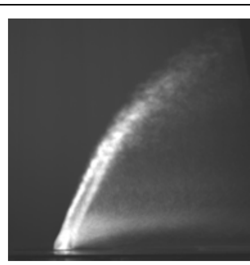
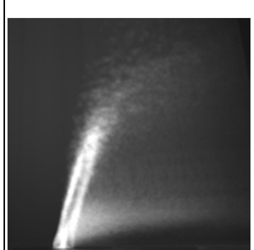
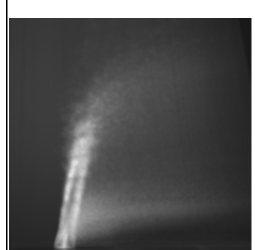
	VR = 2	VR = 3	VR = 4	VR = 5
St = 0.08				
St = 0.11				
St = 0.19				
St = 0.28				
St = 0.56				

Table 2. The structure of twenty round ZNMF-JICF at different Strouhal numbers and velocity ratios.

Results

The mean intensity images of the twenty ZNMF-JICF obtained from the PLIF experiments are shown in table 2. The area of interest is 225 mm x 180 mm which corresponds to 22.5 D_o x 18.0 D_o. The main emphasis is on the structure of the jets and its interaction with the crossflow and hence the analysis is purely of a qualitative nature. As a result the spatial resolution of the flow field is quite low to record the evolution of the complete jet structure. As seen from equation 1, the Strouhal number is a function of amplitude and not the frequency of oscillation of the piston. As seen from table 2, five different St numbers were chosen for a particular VR. The freestream fluid was flowing from left to right as shown in the table. For $0.08 \leq St \leq 0.11$, it can be seen that there is only a primary trajectory of the jet issuing out of the orifice. As the jet penetrates into the crossflow, it bends and tries to align with the freestream fluid. With increase in VR, the ZNMF jet tends to align more axially with the orifice. This is because at higher velocity ratio the jet momentum is more dominant than the freestream momentum and as a result the mean dye concentration in regions away from the jet center increases. In this range of Strouhal numbers, the jet is known as the single trajectory jet by virtue of its solitary trajectory issuing out of the orifice.

As the Strouhal number is increased, there is a definite transition from the single trajectory structure to a multiple trajectory structure. This is shown by the flow visualizations at St = 0.19 in table 2. The primary trajectory is one that penetrates further into the freestream but there is a secondary trajectory that emerges from the primary one forming an acute angle. This angle between the two trajectories increases with increase in VR due to the progressive alignment of the primary trajectory with the axis of the orifice.

For $St \geq 0.19$, there is a well defined multiple trajectory structure. The angle between the two jet trajectories can be seen to be a function of St and VR.

In continuous jets, the trajectory based on the maximum velocity represents the streamline originating at the orifice center. This is not the case with the ZNMF-JICF. This is due to the intermittent formation of the jet with a duty cycle of 50%. For half the jet cycle, cross-flow fluid moves unrestrained through the jet trajectory. Hence, although injected fluid penetrates far into the cross-flow instantaneously, in an ensemble average, the cross-flow fluid at the jet center is displaced from the wall by a much smaller amount.

A quantitative study in [5] shows that the penetration of the jet does not depend on VR and their experiments reported the same penetration for VR = 5 and VR = 30. The results obtained in this study show that increase in VR increases mean dye penetration slightly.

Concluding Remarks

The qualitative nature of twenty ZNF-JICF have been studied for a range of Strouhal numbers $0.08 \leq St \leq 0.56$ and velocity ratio $2 \leq VR \leq 5$. Two definite jet trajectories were found for the ZNMF-JICF when the Strouhal number was varied. A critical range of St was found to lie between 0.11 – 0.19 where the transition from single to multiple trajectory takes place. Single trajectory jets are characterized by a single maximum concentration across the width of the jet along the trajectory while multiple trajectory jets are characterized by multiple regions of high concentration issuing from the orifice.

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