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Unsteady flow motions of an oscillating jet in crossflow

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ABSTRACT

The temporal and spatial variations of the flow behavior and velocity field of an oscillating jet in a crossflow were experimentally investigated. A pulsed jet issuing into a crossflow caused the deflected jet to oscillate. The instantaneous oscillating flow patterns in the symmetry plane at several specific phase angles were identified using smoke flow visualization method. The instantaneous flow velocities were measured using the high-speed particle image velocimetry (PIV) and presented as phase-averaged velocity vectors and streamlines. Owing to the variation of jet exit velocity, the near tube-tip jet column flapped up and down within one cycle of jet pulsation and induced a periodic wavy flow structure in the downstream area. By identifying the variations of near-wake velocity vectors and streamline patterns within one excitation cycle, four characteristic flow modes (*downwash*, *crossflow-dominated*, *jet-dominated*, and *transitional*) were found at different excitation phase angles. Around the mid-oscillation cycle, the wavy flow structure was characterized by two adjacent vorticity concentrated areas of opposite signs in the phase-averaged vorticity contour. The turbulence properties of the excited elevated transverse jet at large jet-to-crossflow momentum flux ratio were larger than those at low jet-to-crossflow momentum flux ratio.

1. Introduction

A jet issuing into a crossflow has been investigated owing to its widespread engineering applications such as film cooling of turbines, control of separated flows over an airfoil, industrial mixing, and pollutant dispersion from effluent stacks. Jet in crossflow is commonly classified into two categories depending on their configurations. The first is a wall-issued transverse jet [1–5] and the second is a stack-issued (frequently called "elevated") transverse jet [6–9]. The distinctive vortical flow structures of a wall-issued transverse jet are subject to the interactions among the jet, jet wake, and wall boundary layer, whereas those of the elevated transverse jet are subject to the interactions among the jet, jet wake, and stack wake. The dominant flow features of the time-averaged flow structure of the wall-issued and stack-issued transverse jets are the counter-rotating vortex pair (CVP) associated with the jet cross-section appearing in the far field and coherent structures evolving along the upwind shear layer of the deflected jet. The dynamics of the CVP and shear-layer coherent structures play an important role in entraining flow from crossflow into jet region. Owing to the jet configurations, the trajectory of the deflected jet and the wake characteristics of these two cases present prominent differences. The dispersion and mixing behaviors as well as the mechanisms of the transverse jets issued from a wall orifice and from an elevated stack therefore do not follow the same dominant patterns.

Several devices have been applied to improve the mixing process of a jet in crossflow by exciting the jet flow, such as a piezoelectric actuator, a solenoid valve, and acoustic excitation. Most studies in this area have investigated the characteristic flow structures, penetration, and spread of a pulsed wall-issued jet in a crossflow [10–17]. Gogineni et al. [10] used piezo electric actuators mounted on the interior walls of a square jet to modulate the shear layer of a wall-issued transverse jet. They observed that manipulating the upstream and downstream segments of the jet shear layer led to an increase in the jet penetration into the crossflow. A solenoid valve operated by a square wave signal with variable frequency, injection time, and duty cycle was used to pulse a wall-issued jet in a water tunnel [11,12]. The penetration of a fully modulated wall-issued jet in crossflow was then characterized in terms of the injection time and duty cycle. The jet structure is influenced by injection time and the distance between the jet puffs

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Nomenclature

d	inner diameter of tube, 0.005 m
D	outer diameter of tube, 0.0064 m
E_{exc}	excitation voltage supplying to loudspeaker
f_{exc}	frequency of acoustic excitation
f_u	frequency of axial velocity oscillation
f_w	frequency of transverse velocity oscillation
R	jet-to-crossflow momentum flux ratio $(= \rho_j u_j^2/\rho_w u_w^2)$
Re_j	jet Reynolds number (=$u_j d/\nu_j$)
Re_w	crossflow Reynolds number (=$u_w D/\nu_w$)
t	evolving time
t^*	dimensionless time evolution (=t/T)
T	period of acoustic excitation
u	instantaneous axial velocity
$\bar{u}$	time-averaged axial velocity
u'	fluctuation velocity in axial direction $(= u - \bar{u})$
u_j	average jet velocity at exit
u_{j0}	jet velocity pulsation at jet exit under zero-crossflow condition
u'_{j0}	rms value of jet velocity pulsation at jet exit under zero-crossflow condition
u_w	crossflow velocity
w	instantaneous transverse velocity
$\bar{w}$	time-averaged transverse velocity
w'	fluctuation velocity in transverse direction $(w - \bar{w})$
x, y, z	Cartesian coordinates with origin at center of jet exit plane
Φ	power spectrum density function of velocity fluctuation
Ω_y	vorticity in flow field $\left(= \frac{\partial \bar{w}}{\partial x} - \frac{\partial \bar{u}}{\partial z}\right)$
ρ_j	density of jet fluid
ρ_w	density of crossflow
ν_j	viscosity of jet fluid
ν_w	viscosity of crossflow

or vortices near the injector is affected by duty cycle. Johari [14] proposed a classification scheme of various flow regimes of a pulsed wall-issued transverse jet in the domain of the stroke ratio and duty cycle. A wall-issued transverse jet forced by acoustic excitation has been investigated in a wind tunnel. Vermeulen et al. [15] shows that acoustically forcing a wall-issued transverse jet produces a significant increase in jet spread, penetration, and mixing. M'Closkey et al. [16] and Shapiro et al. [17] found that exciting the jet at the optimal pulse width and at a low excitation frequency yields the best jet penetration and spread.

Several experimental studies have focused on the characteristic flow behavior and mixing of a pulsed elevated transverse jet. Davitian et al. [18] forced a short elevated transverse jet at an excitation frequency that was 10% of the natural frequency of the shear-layer coherence structure of an unforced transverse jet. They found that the effect of sinusoidal forcing on the jet's penetration and spread is not significant when the jet-to-crossflow ratio is relatively low and when the shear layer is globally unstable. Hsu and Huang [19] and Huang and Hsu [20,21] studied the flow-evolution process as well as the penetration, spread, and dispersion characteristics of an acoustically excited elevated transverse jet in a wind tunnel. The difference in the flow behavior and mixing characteristics between the excited wall-issued and elevated transverse jets at various resonance Strouhal numbers has been reported [19]. Huang and Hsu [20] identified three characteristic flow modes (*synchronized flapping jet*, *transition*, and *synchronized shear-layer vortices*) in the domain of the jet-to-crossflow momentum-flux ratio and excitation Strouhal number. The mixing characteristics of the pulsed elevated transverse jet were significantly improved in the synchronized flapping jet flow mode. Huang and Hsu [21] presented time-averaged velocity distributions measured by particle image velocimetry (PIV).

It has been found that the oscillating jet column forming in the upwind shear layer of a stack-issued transverse jet could enhance the mixing characteristics [19–21]. However, the flow velocity field which dominates the characteristic flow modes and mixing were unclear. The present study aims to investigate the temporal and spatial flow dynamics of the oscillating stack-issued jet in crossflow. The characteristic flow behavior of the oscillating stack-issued jet in a crossflow at several specific phase angles was identified using the smoke flow visualization method. The PIV technique was used to measure the time-averaged and phase-averaged velocity fields of the pulsed stack-issued transverse jet. The time evolution of the qualitative and quantitative flow characteristics was examined and analyzed. With the statistical analysis of velocity field, the turbulence properties along the streamline evolving from the center of the jet exit were discussed. The characteristic velocity fields at various specific phase angles were represented by phase-averaged velocity vectors and streamlines patterns.

2. Experimental methods

2.1. Experimental apparatus

The experimental apparatus and coordinate system are shown in Fig. 1. The experiments were conducted in an open-circuit type wind tunnel with a test section of 30 × 30 × 110 cm. A flow-conditioning section including a honeycomb and four mesh screens was mounted in the upstream chamber for the suppression of the crossflow turbulence. A nozzle with a contraction ratio of 9:1 was used to accelerate the crossflow and to further reduce the turbulence intensities. The crossflow was provided by the flow in the wind tunnel test section. The velocity in the wind tunnel test section could be varied between 0.5 and 15 m/s with turbulence intensity and nonuniformity under 0.25% and 0.4%, respectively. A stainless steel tube with an inner diameter of d = 5 mm, outer diameter of D = 6.4 mm, and length of L = 510 mm was adapted to the tip of a nozzle assembly. This tube was perpendicularly protruded into the test section to serve as a stack. The protruding tube height measured from the test section floor to the tube tip was 160 mm. The blockage ratio induced by the extruded tube to the wind tunnel cross section is 1.2% which is negligibly small. The crossflow velocity (u_w) was measured by a Pitot static tube associated with a high-precision electronic pressure transducer. The crossflow Reynolds numbers, Re_w, based on the outer diameter of the tube and the crossflow velocity were fixed at 1170 and 1710. The flow rate of the jet was detected using a calibrated rotameter. The average exit velocity of the jet (u_j) was subsequently calculated by dividing the measured jet flow rate by the cross-section area of the tube at the jet exit. The jet Reynolds number, Re_j, based on the inner diameter of the tube and average exit velocity of the jet (u_j) was 1000. Consequently, the jet-to-crossflow momentum flux ratios defined by $R = \rho_j u_j^2/\rho_w u_w^2$, where ρ_j and ρ_w are the jet and crossflow densities, respectively, and u_j and u_w are the jet and crossflow velocities, respectively, were fixed at 0.56 and 1.20, respectively. The present work is relevant to the applications of the fluid–fluid mixer and industrial furnace. The jet and crossflow Reynolds numbers of the fluid–fluid mixer are conventionally in