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On the near-field flow structure and mode behaviors for the right-angle and sharp-edged orifice plane jet

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ABSTRACT

The study of flow structures in a sharp-edged and right-angle orifice plane jet was investigated experimentally by means of hot-wire technique and smoke flow visualization. The results indicate that the vena contracta effect depends upon the Reynolds number as well as the geometric configuration of the orifice exit. The vena contracta effect in the sharp-edged orifice plane jet is much significant and to suppress the development of coherent structures. In addition, the sharp-edged orifice plane jet is considered more complexity since two competing initial instability frequencies were found at Re = 10,300 or above. Meanwhile, two types of instability modes exist in the orifice plane jet, i.e. varicose and sinuous mode. These instability modes were observed to depend upon the Reynolds number and geometric configuration of orifice exit as well.

1. Introduction

The upstream nozzle profile effects are ignoring by many researchers in jet flow study. It has been shown that the nozzles with different shape geometry generate prominent changes to the downstream flow [12,13]. Deo et al. [2] confirmed that the effect of the nozzle exit profile with different orifice exit radii on the mean and turbulence field as well as the jet spreading rate.

Experimental evidence revealed that the orifice jet is more complex than those jets from a smooth contraction or contoured nozzle. The exit flow has an inward radial component result of a vena contracta effect and considerable unsteadiness due to the upstream separation [13]. Deo et al. [2] pointed out that the sudden contraction of the orifice jet caused a large and annular flow separation at upstream from the exit plane. It was well known that the flow in such separation region was unstable and usually oscillating. Mi et al. [13] further found that the primary vortices was generated in higher rate in orifice jet than that to the smooth contraction nozzle jet. This was confirmed by Deo et al. [2] as well. According to Mattingly and Chang [11], the varicose mode is dominant in a short distance from the nozzle exit but the sinuous mode is found to dominant at further downstream in theoretical study of the axisymmetric contoured nozzle jet based on the inviscid theory. Ho and Hsiao [7] confirmed that the dominance of the instability modes depends on the jet exit velocity also the transverse location. Hsiao et al. [10] also studied the energy transferring behaviors for the sharp-edged and right-angle orifice plane jet. They found that the kinetic energy gained at immediate orifice exit is contributed by the mean energy advection. The fluctuation kinetic energy implants into the turbulent flow through turbulent energy advection at the vortex merging process.

The extant literatures are rare in adopting the orifice profile and most of the previous studies on the jet flows related predominant to those from smooth contraction nozzle. Nevertheless, jets from orifice are still widely used in manufacturing. However, more recent studies of orifice jets are focused on the circular and elliptical orifice jets (e.g. [13,15]. It is worthwhile to pay more attention to the two-dimensional orifice plane jet. The present study aims to investigate the near-field flow structures of orifice plane jets.

2. Experimental arrangements

The air supply facility consists of a noise reduction chamber together with an open circuit tunnel, including diffuser and settling chamber. The noise reduction chamber is designed to reduce the passage noise generated from the blower. A honey comb and eight fine screens are deployed so that the exit turbulence intensity is low under operating velocity range of $U = 5/20$ m/s or $Re = 5.15 \times 10^3/2.06 \times 10^4$, based on the orifice exit height. In addition, the orifice plates of current study were mounted at settling chamber and different from the previous studies, which are usually installed at the smooth contraction nozzle exit as shown in Fig. 2. The orifice plates are fabricated by aluminum plate with the

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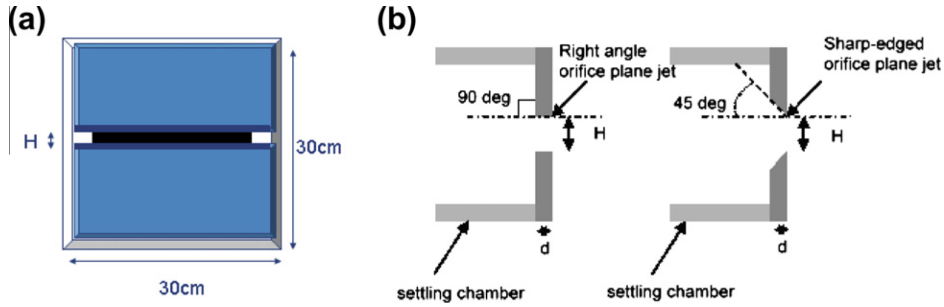

Fig. 1. (a) Schematic representation of orifice plane jet. (b) Side view of right-angle and sharp-edged orifice plane jet.

thickness of 6 mm. The angle of orifice plate is defined between the horizontal lines (parallel to ground) and the tip of plate, therefore the angles of sharp-edged and right-angle orifice plate in present study are equal to 45° and 90°, respectively (see Fig. 1). The height of orifice is set to 15 mm, therefore, the aspect ratio is 20. The measurements of the flow field are performed by using two DISA 55M01 constant temperature anemometers. A cross-type hot-wire probe used simultaneously on measuring the streamwise and transverse velocity components of the jet flow.

For the flow visualization study, the smoke is generated by smoke generator in inlet muffler and is ejected from the orifice by driving of a blower. The flow structures are visualized by laser-light sheet and smoke flow. A diode-pumped solid-state (DPSS) laser beam is spread out to be a laser sheet by a cylindrical lens. The flow patterns are captured by a high-speed video camera (IDT) with frame rate of 1000 Hz. This means that each picture shown in this paper is captured at an instant of 0.001 s. In order to study the influence of the Reynolds number on the development of flow structures in sharp-edged and right-angle orifice plane jet, thereby the flow visualization is undertaken at velocity of 7 m/s, 10 m/s and 15 m/s. Note that the black and white marker in the each photo equals to 15 mm or $X/H = 1$ from the orifice exit.

3. Results and discussion

3.1. Vena contracta effects of the orifice jet

Generally, the evolution and interactions of the coherent structures are recognized to be dominant in the jet column. However, the jet cross section at immediate exit of orifice does not coincide with the orifice. This phenomenon is called vena contracta effect or contraction (see Fig. 3), which was first pointed out by Mi et al. [13]. This phenomenon is due to the fact that the fluid inside the vessel flows radially towards the orifice and, when it reaches the edges, it cannot immediately turn from the radial direction into the direction of the axis [14]. The cross section at which the jet becomes parallel is referred to as vena contracta, normally the jet cross section at this location shrinks to the minimum. However, the cross section of the jet at immediate orifice exit will then be almost equal to the orifice if a rounded-off opening is deployed where the change of the streamlines is completed within the mouthpiece.

The vena contracta effect really plays an important role on the downstream development of the jet flow. However, no extensive study was discussed on the relation of Reynolds number to this effect. Figs. 4 and 5 depict the downstream development of centerline and peak of streamwise mean velocity, which are normalized by the jet exit velocity. It is obviously to see that the flow is accelerated $\left(\frac{U_C}{U_0}, \frac{U_p}{U_0} > 1\right)$ as issuing from the orifice, particularly in sharp-edged orifice plane jet. This behavior is dictated by the vena contracta effect as flow must suffice mass continuity equation. As a result, the shrinking of the jet cross section at immediate exit of orifice renders the flow to accelerate perforce. Accordingly, it can foreshadow an acute vena contracta effect in sharp-edged orifice plane jet. It is indicated that the orifice exit profile is one of the factors to alter the vena contracta effect, i.e. the flow moves along the sharp-edged (45° beveled) walls on the orifice exit and this profile leads the jet to shrink more at the immediate exit

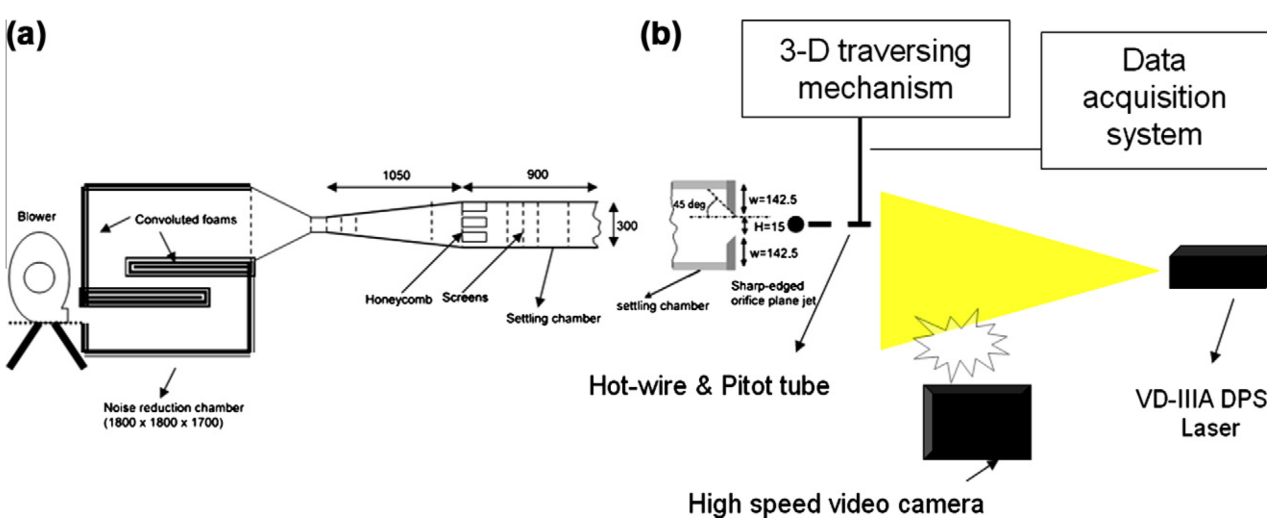

Fig. 2. (a) Experimental layout of the sharp-edged orifice plane jet (mm). (b) The experimental set-up of flow visualization and measurement system.