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Interaction of a vortex ring with a cutting thin plate

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ABSTRACT

An experimental study was made on symmetrically cut of a vortex ring by a finite length thin plate. The interaction was studied to evaluate flow features using volumetric three component flow velocimetry (V3V) system. Vortex rings were generated using a piston-cylinder mechanism at jet Reynolds numbers of 1500 and 2000 with piston stroke length-to-diameter ratios of 2 and 3. Experiments were made for the plate thickness of 0.86 mm, plate length to diameter ratio of 0.13 and 0.536, and with a cut of vortex ring on the centerline and below the centerline. The interaction of vortex ring with plate showed strong dependence on cutting depth. For the case of cutting below the centerline of the vortex ring showed formation of the three vortex rings. One moved in the same line as the primary vortex ring and other two moved perpendicular to the plate (one in each side with respect to the centerline of the primary vortex ring). On the other hand, for the case of the vortex ring cut up to the centerline axis showed generation of a centerline vortex ring with a vortical structure circulating around the vortex ring loop.

1. Introduction

A sudden initiation fluid inside a jet nozzle by piston leads to the formation of a toroidal vortex at nozzle exit which is also called vortex ring at nozzle exit. Aspects of vortex ring formation and evolution were extensively reviewed by Shariff & Leonard [1] and Lim & Nickels [2]. Vortex rings can be observed in variety of not only engineering and biological applications but also potential and some available use of it in engineering applications like swimming devices [3–6] and cooling of electronics [7,8]. One of the common method for generating vortex rings is a transient jet ejection from a tube or orifice [1,2]. The key parameters of characterizing the vortex rings are ejected amount of jet which includes ratio of length of piston travel inside the tube to tube diameter (L/D), Reynolds number (Re) based on D and the maximum speed of the jet, U_{max}. The usual evolution of these ring properties in the flow can be changed significantly by the presence of the downstream object and ring properties. Interactions with solid objects tend to alter the vortex core trajectories and redistribute the momentum and energy of the flow field.

There are several studies in vortex ring imaging on orthogonal or with an angle to the wall to the wall [9–15]. Orthogonal to the wall interaction shows that when vortex ring getting closer to the wall its diameter increases and opposite sign secondary vorticity are generated on the wall. For higher Re boundary layers separate and form a secondary vortex ring [9]. Interaction of the primary and secondary vortex ring leads to move of the vortex ring to the opposite direction. For higher Re tertiary rings can be also observed near the primary vortex rings [10]. For the case of oblique interactions, at an angle of 38.5° interaction, secondary vorticity generated around vortex ring which show asymmetry compared to the normal to wall interactions and becomes complex three dimensional flow structure [13,14]. Coach & Krueger [15] made experimental study at oblique angles of 0–60° and at jet Re of 2000–4000. It was observed that for oblique angles of lower than 20° positive vorticity generated near

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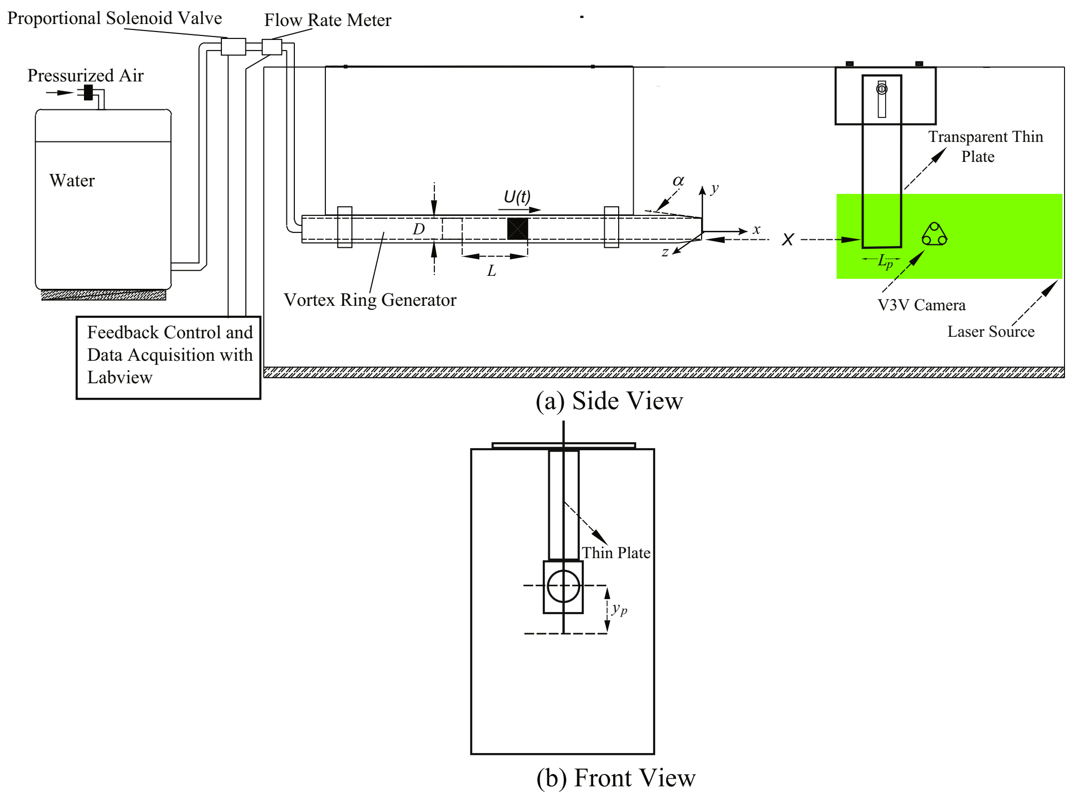

Fig. 1. Schematic of experimental set up.

the wall, but for higher angles upstream of primary flow negative vorticity also generated and lower portion (which subjected to the no slip boundary condition) of the ring experience rebound. Asymmetry and dissipation generated from lower portion of the vortex ring and flow dissipation rate increased as the *Re* increase.

Although several studies were made on vortex ring interaction with orthogonal and oblique interaction with the plate, studies on vortex ring interaction with cutting plate or edge of the plate were limited. Two dimensional numerical study was made on vortex dipole and plate tip interaction [16]. It was shown that as vortex dipole come closer to the plate vorticity generated on the plane and upon impact the primary dipole split into complex vortical structures, including secondary and tertiary vortex pairs. The vorticity magnitudes of the fluid structures of secondary and tertiary vortex pairs were generally unequal. Complexity of the flow features shows that three dimensional flow analysis is needed to understand the flow. Weigand [17] made an extensive experimental study on vortex ring cutting plate interaction using flow visualization techniques with the support of the quantitative flow measurement techniques of Digital Particle Image Velocimetry (DPIV) and Laser Doppler Anemometry methods. In his study the effect of cutting plate depth (y_p) at $-10 \leqslant y_p/D \leqslant 3$, thin plate length ($L_p$) at $0.04 \leqslant L_p/D \leqslant 15$, and Reynolds number of the initial vortex ring, $Re_\Gamma = \frac{\Gamma}{\nu}$ (where Γ is circulation and ν is kinematic viscosity) $900 \leqslant Re_\Gamma \leqslant 1700$ were investigated. Five different flow regimes were observed depends on the *Re* and plate properties. For cutting depth of $0.066 \leqslant y_p/D$ (positive y_p/D means above the center of the vortex ring generator) at $900 \leqslant Re_\Gamma \leqslant 1010$ and $0.04 \leqslant L_p/D \leqslant 1.5$, presence of the plate did not affect the vortex ring generation and axial flow oscillations observed. For experiments made in the ranges of $-0.066 \leqslant y_p/D \leqslant 0.066$, $0.04 \leqslant L_p/D \leqslant 1.5$ regular flow patterns were observed due to the fact that flow was dependent on the initial conditions; for lower *Re* cases initial vortex ring spitted into the two or more smaller vortex rings lead to irregular vortex line pattern and for some cases after interaction vortex ring covered and new vortex ring formed further downstream and, for higher *Re* small scale week vortex structures were formed and new vortex ring developer. For the vortex ring cut below the center line with cutting depth of $y_p/D < -0.066$ three distinct flow cases were observed depend on the initial conditions. For $Re_\Gamma = 900$, $L_p/D = 0.5$ and $y_p/D = -0.33$, after the interaction with thin plate three vortex rings were formed. Two vortex rings propagated symmetrically normal to and away from the plate and the third vortex ring propagated in the same direction as the initial vortex rings. This process was called trifurcation by Weigand [17]. For higher $1100 \leqslant Re_\Gamma \leqslant 1700$ cases trifurcation was reported to be formed for shorter plate lengths $0.04 \leqslant L_p/D \leqslant 0.5$. For $Re_\Gamma = 1100$, $L_p/D = 0.5$ and $y_p/D \to -\infty$ (-10) case, rather than three vortex ring, a vortex system of closed two