International Journal of Structural Analysis & Design – IJSAD
Volume 1 : Issue 1
Publication Date : 09 January 2014

Transition map for vortex rings over an axial rod

Swarandeep Sahoo, Prafulla Sohoni and Debopam Das
Department of Aerospace Engineering
Indian Institute of Technology Kanpur
Kanpur, India

***Abstract*—Vortex rings are one of the most robust and fundamentally important fluid-structure in vorticity dominated flows. The rolling up of a slug of fluid mass, impulsively pushed out of an orifice, is generally stable. Owing to proposition of many applications of such flows, in the present study, an attempt has been made to characterize the nature of formation of vortex rings formed due to orifice in the presence of an axial rod. Experimental investigations are carried out to find the conditions under which the generated vortex ring is initially laminar or turbulent for various parameters. The results are used to draw a transition map pointing out the regions of different flow behavior.**

***Keywords*—Vortex Rings, transition map, cylindrical rod**

I. Introduction

The study of vortex rings has received impetus for long on account of its fundamental importance to vorticity dynamics as well as to numerous natural and man-made applications. The dynamics of the rectilinear counterpart of such a structure, namely line vortices have been utilized in the modeling of tornadoes and hurricanes. For the case of ring vortices, applications such as pollution transport from chimneys (Shariff & Leonard (1992)) and to extinguish fires at gas and oil wells (Akhmetov et. al. (1980b)) requires a thorough understanding of the formation characteristics of such flows.

Vortex rings are usually generated in the laboratory by impulsively pushing a slug of fluid through a sharp edged orifice or a nozzle. Utilizing the properties of vortex rings, Lucey, Jr *et al* (2003) have proposed effective ways to produce useful work using vortex rings. In their invention, a concentric rod is placed along the axis of propagation of the vortex ring with the aim of using the high axial momentum of the central region for the removal of surface deposits on a tube and also, as a heat exchanger where heat is transferred from a heated tubular plate to the vortex ring that carries it to a heat sink.

It can be understood that for efficient operation of such devices, the nature of the vortex rings formed play a crucial role. The parameters governing the formation process relate to the amount and the duration of time over which the fluid is ejected. The separating flow at the edge possesses different characteristics for different generating conditions.

The above phenomena is well analyzed in an investigation carried out by Glezer (1988), where he points out the conditions under which a given vortex ring generator will produce a laminar ring or a turbulent one. It is worthwhile to note, that, a vortex ring which is initially laminar undergoes formation of wavy disturbances on its core during its evolution. These disturbances grow in amplitude and subsequently lead to the breakdown of the vortex ring.

In the light of Glezer's work on transition map for vortex rings, the present study is concerned with understanding the role of different exit geometry, i.e., an annular hole in a plane, in affecting their formation characteristics. We delineate the conditions for the formation of initially laminar or turbulent rings for the exit geometry similar to that of Lucey *et al*. To this effect, an experimental study of formation of a vortex ring in the presence of an axial rod is carried out in order to assess the effectiveness of operation of such vortex generators.

II. Experimental Arrangement

The apparatus used for generation of vortex ring in a controlled manner is shown in Fig. (1). A tank of square cross section, measuring 0.5 m by 0.5 m, and 2 m long is divided into two compartments. The plate is placed at a distance of 0.5 m from one end forming the "driving section". A flat rectangular piston is attached to one of its ends. The other compartment is used as the "test section" for observing the formation of vortex rings and its further dynamics. This arrangement facilitates in leaving all electronic equipment outside the testing region in order to prevent undesired air motion produced by them.

A thick polystyrene sheet is used as the piston, which is attached to and driven by a loudspeaker (100 W). The piston almost fits the walls of the chamber with the gaps sealed using flexible polythene strips. This allows a smooth and unobstructed motion of the piston against the walls without rubbing on its surface, at the same time, ensuring a leak proof arrangement.

The loudspeaker is driven by a forcing signal that is first synthesized and stored in the non-volatile memory of an arbitrary function generator. This moves the connected piston which in turn displaces a slug of air volume through an orifice. A TTL trigger signal from the NI-DAQ (NI USB 6210) card is used to trigger the signal generation which is then amplified by a power amplifier and fed to the speaker.

The distance moved by the piston is denoted by "Stroke Length" (L_P) while the time taken for the piston to push the fluid is denoted by "Stroke Time"(T_P). In practice, " L_P is determined by the signal 'peak to peak' voltage range while T_P is determined by the rise time of the signal. The displacement of the piston is tracked from images taken using a high speed camera operating at 100 Hz frame rate.

The configuration for studying the formation process in the presence of the rod was made by placing a cylindrical glass

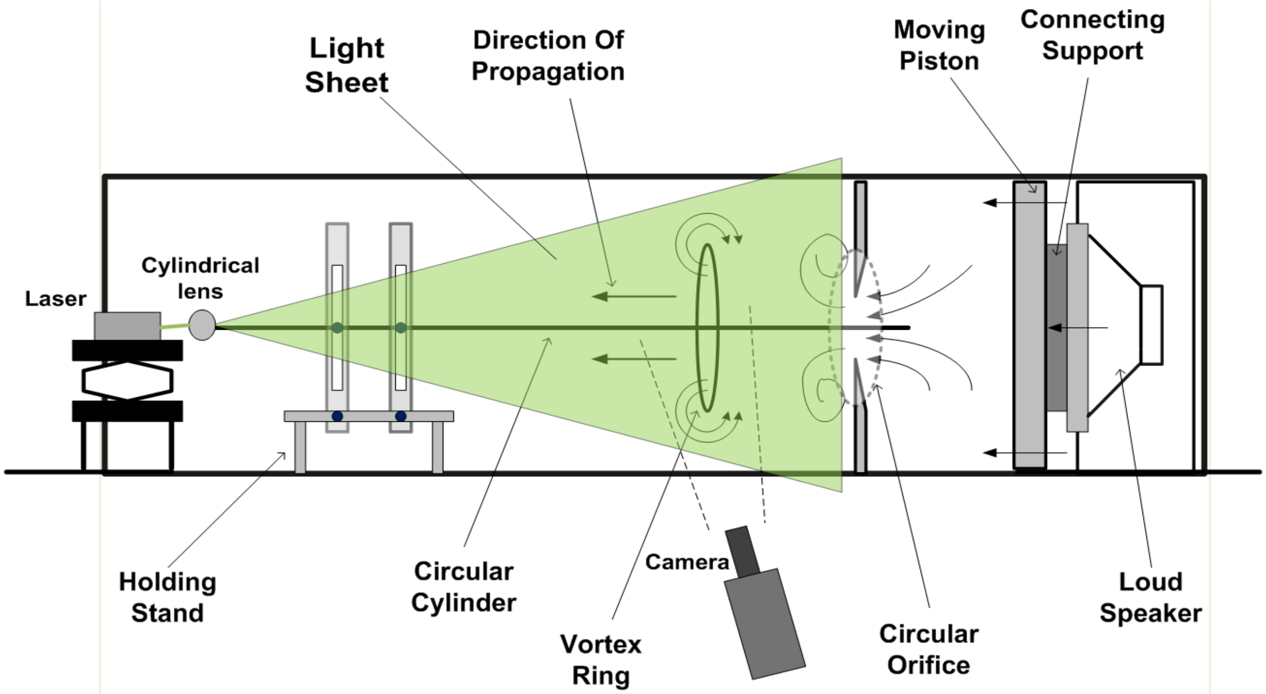

Figure 1. Schematic diagram of the experimental setup.

rod along the axis of the orifice. The rod is held by a stand and positioned such that approximately $2D_O$ of its length is inside the exit. Thus, the flow starts interacting with the rod as soon as the piston pushes some fluid out of the annular hole thus formed. The complete set-up for flow visualization experiments is also depicted in Fig. (1). For a detailed study, 5 rods and 3 orifices of different diameters were used.

A continuous laser (1.2 W) and a high speed camera of resolution 1028 * 1296 pixels is used to visualize the flow seeded with smoke particles. The laser sheet, created using a cylindrical lens is made to lie in a vertical plane passing through the rod's axis. Due to refraction from the edges of the cylindrical rod, the light sheet had lines of shadow region developed onto it. In order to tackle this problem either we have taken image for one half of the ring or sometimes we forsake capturing areas close to the surface of the rod.

III. Observations

At the start of piston motion, flow separates at the orifice edge and begins to roll-up. This marks the start of the formation process for the vortex ring. The presence of rod along the axis causes the flow over it to develop an unsteady boundary layer as more and more fluid is pushed out. During the piston motion, which is impulsive in nature, both the above processes occur simultaneously.

Different configurations of the exit geometry based on a rod and an orifice size, result in a varied nature of the vortex ring roll-up. Broadly, two types of scenarios can be easily identified. One is the case of smooth roll-up of the cylindrical shear layer into a spiral. This is identified as an initially laminar ring that is characterized by less disturbed feeding jet, which eventually gets detached from the forward moving vortex ring.

On the other hand, for some cases, the flow ejecting out of the exit is initially much disturbed. Besides the primary vortex ring being highly disturbed, there occurs continuous shedding of smaller vortices from the orifice edge. The smaller scale shedding introduces wavy disturbances into the shear layer that subsequently get entrained into the vortex ring. This causes the vortex ring to undergo quicker distortion, as compared to a laminar ring, and rapidly lose its spiral structure. The trailing jet in these conditions is not completely entrained rather; it undergoes shear layer instability forming a trail of smaller rings. Such vortex rings do not exhibit a well formed spiral structure and may be classified under an initially turbulent vortex ring.

In either of the above conditions depicted more clearly in the flow visualization images of Figs. (2 & 3), the effect of the presence of the rod come into play due to the formation of secondary vortex ring due to unsteady separation of the axisymmetric boundary layer. For the turbulent vortex rings, the secondary vortex ring is rapidly entrained into the primary one, causing further distortion to the vortex ring. But, for the laminar rings, entrainment of the secondary vortex is smoother, producing lesser disturbance to the evolution of the primary ring.

IV. Results and Analysis

In order to depict the detailed experimental survey, the parameters affecting the flow conditions during the formations process were identified. The most important among them is total mass of the fluid pushed by the piston. This quantity is

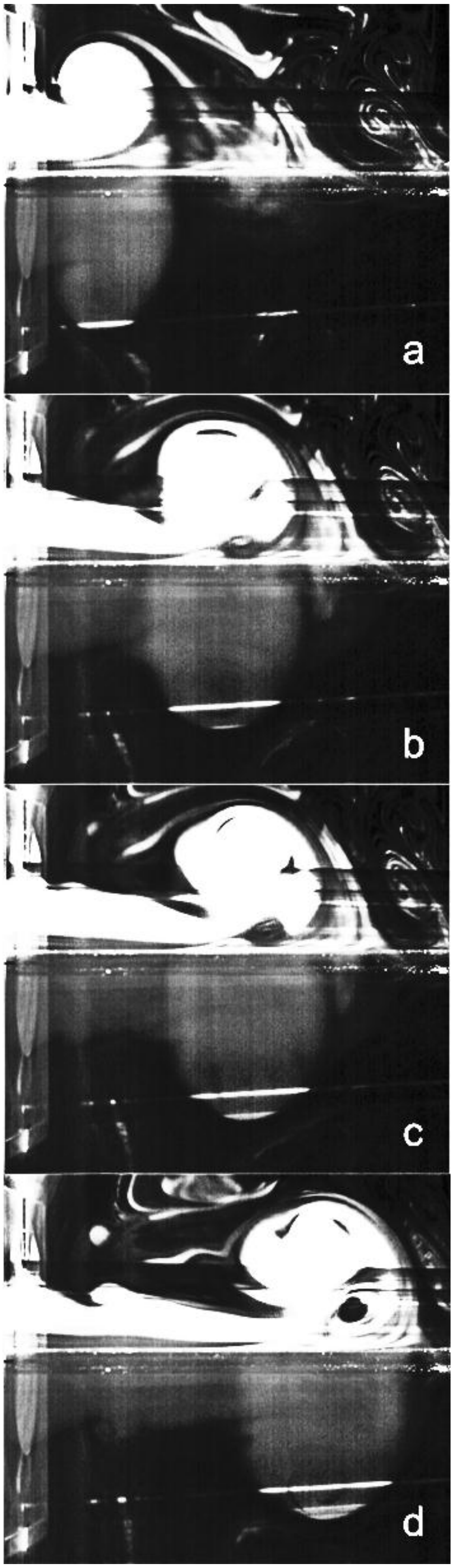

Figure 2. Flow visualization images depicting the formation of an initially turbulent vortex ring over a rod. [Case corresponding to "A" in Re_{Jet} - ε plot depicted in Fig. (5).]

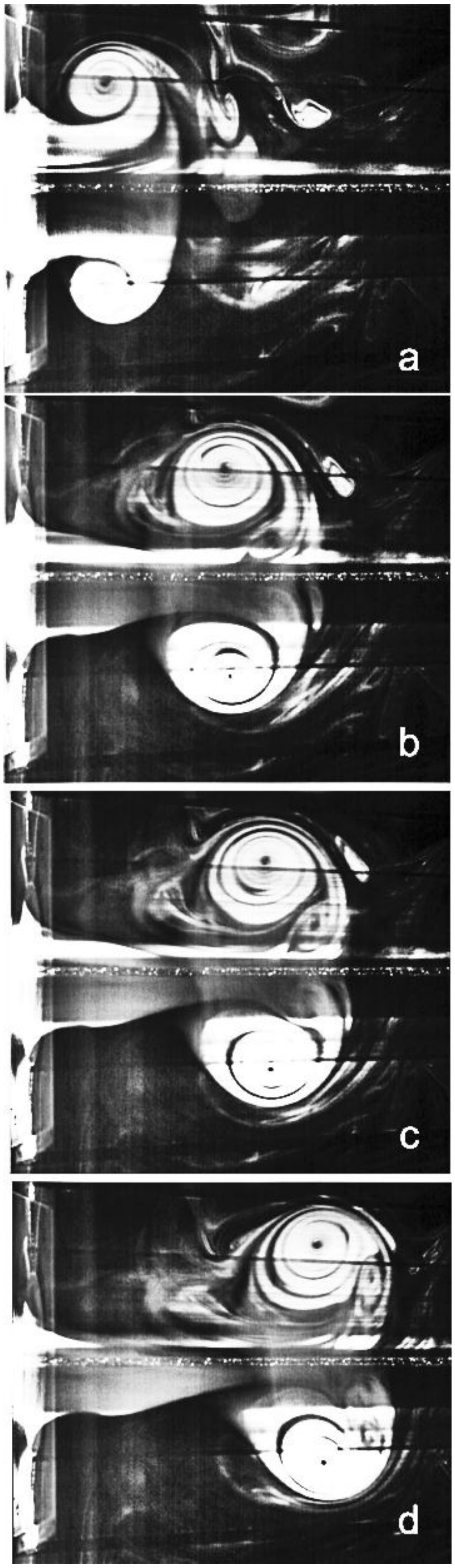

Figure 3. Flow visualization images depicting the formation of an initially laminar vortex ring over a rod. [Case corresponding to "B" in Re_{Jet} - ε plot depicted in Fig. (5).]

determined from the Stroke length and area of the piston. The fluid motion is also dependent on the duration of the piston displacement, hence stroke time. Thus, the nature of the impulsive starting flow is represented by the first non dimensional quantity, Re_{Jet}, the jet Reynolds number.

We hereby point out that, the relative contribution of flow inertia trying to move the vortex ring ahead and the viscous effects inducing the shear layer roll-up with boundary layer formation, is depicted by this quantity. Based on the diameter of the orifice, D_O is defined as:

$$Re_{Jet} = \frac{U_M D_O}{\nu} \qquad (1)$$

where ν is the kinematic viscosity of air at 30°C (temperature at which the experiments are performed). (U_M) is the average ejection velocity defined as:

$$U_M = \frac{L_P}{T_P} * \frac{A_P}{A_O} \qquad (2)$$

Where A_P is the area of the piston and $A_O = \frac{\pi}{4} D_O{}^2$, the exit area. In terms of piston motion quantities that are measured directly from the experiment, jet Reynolds number is obtained as:

$$Re_{Jet} = \frac{4\, L_P\, A_P}{\pi\, T_P\, \nu\, D_O} \qquad (3)$$

A list of cases along with the corresponding stroke lengths and stroke time, and hence, Re_{Jet}, is given in Table (2).

Moreover, it was felt necessary to conduct the experiments for various diameter orifices and rods to understand the effect of the size and shape of the solid boundaries of the formation process. Thus, we define a geometrical non-dimensional quantity ε as:

$$\varepsilon = \frac{D_{rod}}{D_O} \qquad (4)$$

Where, D_{rod} is diameter of rod and D_O is the diameter of the orifice. This, indeed, reflects the dependence of the initial characteristics on the exit configuration as well as the fluid boundary interactions on the flow conditions not only at the formation but also during the interaction of the separated boundary layer with the vortex ring. The values of ε for different configurations are listed in Table. (1).

The results are depicted in the transition map shown in figs. (4 to 6) for different orifice sizes. We observe the respective zones, represented by the values of Re_{Jet} versus ε, for which a vortex ring formed is initially laminar or turbulent. Given an orifice, it is evident that vortex rings are turbulent for high values of both the non dimensional quantities and laminar for relatively lower values. A glance over the results for all three orifices gives the relative shift of laminar zone in the Re_{Jet} - ε plane. The effect is that with increase in the orifice diameter, both the laminar as well as the turbulent zones shift away from the origin.

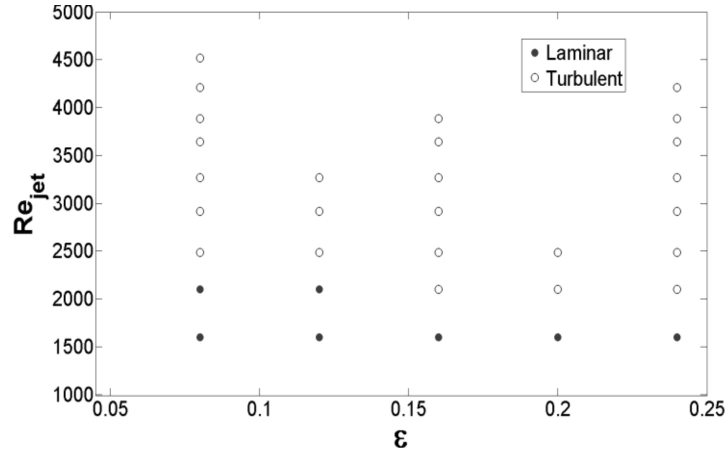

Figure 4. Transition map for 50mm diameter orifice.

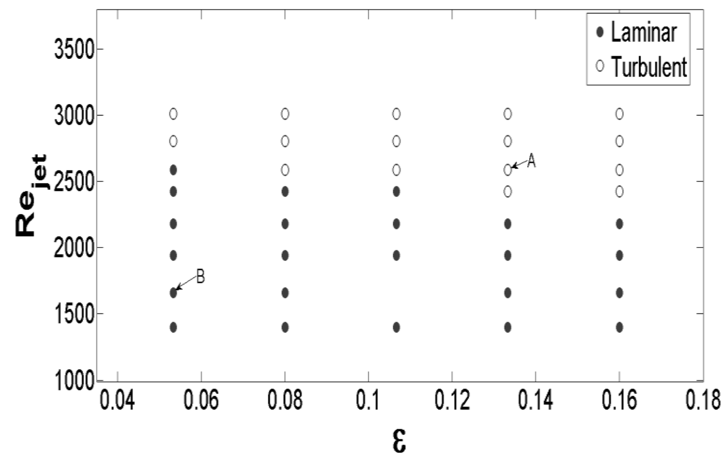

Figure 5. Transition map for 75mm diameter orifice.

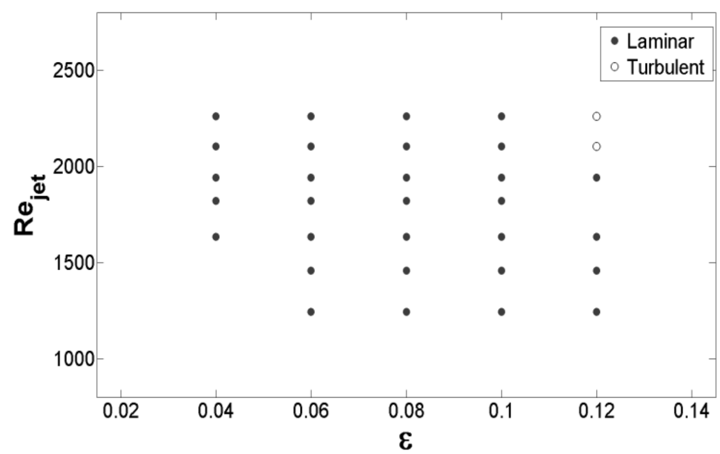

Figure 6. Transition map for 100mm diameter orifice.

V. Summary and Conclusions

The prime motivation of this work is to study the nature of vortex rings during the early part of their formation. The geometrical configuration is chosen following the recently invented vortex generator for industrial applications as mentioned earlier. The flow evolution is captured using flow visualization using smoke.

The study reveals the existence of two categories of initial behavior, initially laminar or turbulent, as observed by earlier studies in this regard with a simpler exit condition. The effect of boundary layer formation and its unsteady separation on the formation process is also realized as one of the important phenomenon affecting the flow evolution.

As part of the study, the parameters governing the flow are identified. The results depicted using non-dimensional quantities formed from these parameters depict the conditions under which a vortex ring formed is either laminar or turbulent during its formation phase.

From the point of view of industrial applications involving heat transfer, the generating conditions should be such that it can be placed away from both axes in the Re_{Jet} - ε plane. This ensures rapid mixing due to turbulent nature of the flow and improves the efficiency of the purpose. Unlike this, for particle transport applications, it would be more appropriate to employ the conditions so as to be situated near to the origin in the Re_{Jet} - ε plane. The vortex rings are more robust with efficient entrainment properties. Also, the loss of vortical fluid to the ambient is minimal ensuring better transport rather than spread of particles.

Table 1. Values of ε for various exit configurations.

D_{rod}	D_O	ε	D_{rod}	D_O	ε
4	50	0.080	8	100	0.080
4	75	0.053	10	50	0.200
4	100	0.040	10	75	0.133
6	50	0.120	10	100	0.100
6	75	0.080	12	50	0.240
6	100	0.060	12	75	0.160
8	50	0.160	12	100	0.120
8	75	0.107			

D_{rod} *and* D_O *are* measured in mm

Table 2. Jet Reynolds no. for 75 mm diameter orifice.

Case	L_P (mm)	T_P (ms)	Re_{jet}
1	83.5	285	1401
2	105.8	305	1659
3	128.0	315	1944
4	150.3	330	2178
5	172.5	340	2427
6	194.8	360	2588
7	217.1	370	2806
8	239.3	380	3013

References

[1] K Shariff, and A Leonard, "Vortex Rings." Annual Review of Fluid Mechanics,1992 Vol. 24: 235-279.

[2] D.G. Akhmetov, B.A. Lugovtsov, V.F. Tarasov, "Extinguishing gas and oil well fires by means of vortex rings." Fiz. Goreniya Vzryva, 1980b Vol. 5: 8-14.

[3] A.Glezer, "The formation of vortex rings." Phys. Fluids, 1988 Vol. 31: 12.

[4] G. K. Lucey Jr., T. Gher, G. Cooper, R. J. Richter, "Methods for using a ring vortex." United States Patent,2003, US006544347B2.,