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Influence of After Body Shape on the Performance of Blunt Shaped Bodies as Vortex Shedders

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Abstract**—**The present study explores flow visualization experiments with various blunt shaped bluff bodies placed inside a circular pipe. The bodies mainly comprise of modifications of trapezoidal cylinder, most widely used in practical applications, such as vortex flowmeters. The present configuration possesses the feature of both internal and external flows with low aspect ratio. The vortex dynamics of bluff bodies in such configuration is seldom reported in the literature. Dye injection technique is employed to visualize the complex vortex formation mechanism behind the bluff bodies. The influence of orientation, slit and after body shape is studied in an attempt to obtain better understanding of the vortex formation mechanism. Various wake parameters like Strouhal number, vortex formation length and wake width are documented for these shapes. Vortex formation both with and without shear layer interaction is observed for most of the shapes.

Keywords**—**Flow visualization, Reynolds number, Strouhal number, vortex, vortex formation length, wake width.

I. INTRODUCTION

FLOW visualization has played an important role in the development and understanding of fluid dynamics, unveiling many important phenomena, which were developed theoretically later. Vortex shedding was observed first by Benard (1908), who observed the alternate precision of eddies behind a towed circular cylinder in water, based on the visible dimples on the water surface [1]. Flow visualization not only provides qualitative insight into the flow parameters, but further opens the way for other research, using numerical simulations and the experimentation. Though the phenomenon of vortex shedding was observed almost a hundred years ago, the research in this field is restricted to the two dimensional bluff bodies with low blockage ratios. Most of the research in the past is centered around circular cylinders and only some specific knowledge of particular bodies other than cylinder is known till date. Cylinder is the most widely studied bluff body among all the other vortex shedders. The reason behind is the abundance of cylindrical structures all around us that are exposed to fluid flows. Sharp edged bodies have also gained attention from many researchers, because of its use in various practical purposes like flowmeter, vortex generator, energy harvesting devices etc. Among sharp edged bodies, trapezoid is reported to be a strong and stable vortex generator. Considerably fewer efforts have been made to go beyond the sphere of these two basic structures and come out with another bluff body that can over perform the two conventionally well-established bluff bodies in this field.

Igarashi [2] investigated the effect of slit in a vortex shedder placed normal to the flow direction, and compared the results with trapezoid and cylinder. The results indicated that a circular cylinder with a two dimensional slit, along the diameter resulted in highly stable and strong vortices with the blockage ratio of 0.2 - 0.3 [2]. Gandhi et al. [3] used computational fluid dynamics for various shaped bluff bodies to find out the best vortex shedder and concluded that a flowmeter requires a body with sharp edges to generate strong and stable vortices. Kamemoto et al. [4] investigated qualitative three dimensional features of a cylinder and a trapezoid in a circular pipe, using flow visualization.

Not many results and understanding of blunt vortex shedders have been developed for circular pipe flow. The results for a channel flow and a circular pipe flow may differ tremendously, as the tunnel exhibits a two dimensional domain while circular pipe flow features three dimensionality. Hence, the objective of the present work is to study the vortex dynamics of the unconventional shapes placed inside a pipe.

In this context, the after body shape effects have been investigated in this paper for a trapezoidal bluff body. The after body shape in general refers to the shape of the bluff body after the separation point. The introduction of slit in a cylinder is known to increase the strength and stability of vortex shedding as shown by Igarashi [2]. On a similar track, the effect of introducing a slit in a trapezoidal cylinder is captured in the present study.

Thus the broad objective of the present study lies in getting fundamental insights in to the properties of the novel unconventional bluff bodies, which may find potential applications in practical purposes as well.

II. EXPERIMENTAL SETUP

All the experiments were conducted in a specially designed set up for laminar flow with water as the working medium. A transparent circular pipe with inner diameter $D = 54\ mm$ was used for conducting all the experiments. The present study is restricted to laminar flows i.e. $Re_D < 2300$. The water is supplied from an overhead tank in which the water level is maintained constant using an overflow line, for assuring constant flow rate during the experiments. A pump of power 1 *HP* is used to feed water to the overhead tank. The mass flow rate is measured using a Micro Motion Coriolis flowmeter with least count of 0.0001 *g/s* The flow rate from the tank is controlled using two valves, one coarse and other for fine adjustment of the flow. The setup is shown in detail in Fig. 1.

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The flow rate through the pipe is restricted to 100 *g/s*, i.e. Re_D = 2360. Sufficient upstream length is provided upstream to the vortex shedder to ensure fully developed flow conditions. For visualization, a carefully controlled amount of dye is injected through needles of 0.8 *mm* outer diameter, without disturbing the flow. The dye used is concentrated $KMnO_4$ (Potassium Permanganate) solution. The dye is injected into the flow from two openings of 0.8 *mm* diameter, at the center of the length of the vortex shedder. The two dye injection points were located on the frontal face or near to the separation points/sharp edges respectively. The gravity feed method is employed to inject the dye into the flow. The amount of dye is adjusted for each flow rate using valves to minimize the diffusion and to get better view of the shed vortices.

The region important for observing the vortex shedding phenomenon is the wake region up to 5*D* downstream of the vortex shedder. Videos of duration 120 *s* were captured for each flow rate/Reynolds number individually using a Canon digital DSLR Camera, with a resolution of 1280×720 at the rate of 60 frames per second. The region of interest is illuminated with white light of a Compact Fluorescent Lamp (CFL) to increase the contrast and the visibility of the vortices.

III. DATA REDUCTION

The images were extracted from the flow visualization videos, which were processed using commercial software MATLAB. The frequency is obtained from the video by finding out the number of vortices passing through an appropriate point in the image in a unit second. The bluff body width (*d*) is taken as the characteristic length and the average flow velocity (U_m) as the characteristic velocity.

Non dimensional frequency *St* can be calculated using the relation (1)

$$St = \frac{fd}{U_m} \qquad (1)$$

St is calculated with an overall uncertainty of 3.33%.

The streamwise distance between the front separation point and the point where the vortex is about to shed from the shear boundary layer, is taken as the vortex formation length (*L'*).

Flow separation point for the blunt bluff bodies is usually fixed at the sharp edges. The separation point is taken as the reference point for calculation of the vortex formation length for all the bluff bodies. Wake width is defined as the maximum vertical distance between the two shear layers. The centroids of the concentrated dye traces, that represent the vortices, have been used for the calculation of vortex formation length as shown in Fig. 2. The vortex formation length and the wake width were calculated by averaging the respective quantities obtained from all the separate images extracted from the videos.

To reduce the errors due to reflection of light from the pipe walls, a reference image is used that is subtracted from each individual image, before analysis. This reference image is taken in a flow without injecting the dye. The image quality is further improved by contrast and brightness adjustment in addition to histogram equalization.

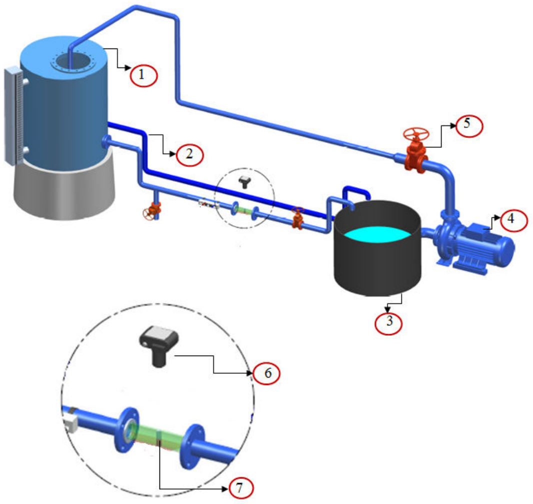


Fig. 1 Test facility for flow visualisation experiments 1. Constant Head Tank; 2. Overflow Line; 3. Gate Valve; 4. Pump; 5. Gate Valve; 6. Camera; 7. Bluff Body

TABLE I
NOMENCLATURE

Symbol	Quantity
A	Cross sectional area of pipe (m^2)
b	Blockage ratio (d/D)
D	Inner diameter of circular pipe (m)
d	Projected width of bluff body (m)
F	Frequency of vortex shedding (Hz / s^{-1})
l	Streamwise length of vortex shedder (m)
L	Body length of vortex shedder (m)
L'	Vortex formation length (m)
R	Radius of curvature of the concave notch (m)
s	Slit width (m)
U_m	Mean velocity (m/s)
W	Wake width (m)
X	Stream wise coordinate (m)
Re_D	Reynolds number $\left(\frac{\rho U_m D}{\mu}\right)$
St	Strouhal number $\left(St = \frac{fd}{U_m}\right)$
ρ	Density of fluid(kg / m^3)
μ	Dynamic viscosity of fluid ($Pa.s$)

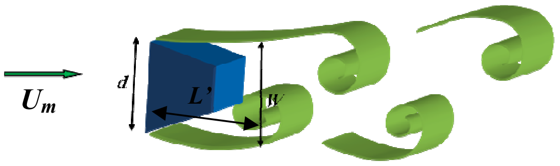


Fig. 2 Flow Parameters [5]

IV. BLUFF BODIES

The bodies chosen for the study are modifications of trapezoid, inspired by previous studies [5], [6]. The influence of orientation, slit and after body shape is studied in an attempt to obtain better understanding of the vortex formation mechanism. The longitudinal length of the vortex shedders equals the inner diameter of the circular pipe i.e. $D = 54$ *mm* i.e. the blockage ratio is same as the aspect ratio. The geometric details and the naming scheme are shown in Table II. The geometrical parameters and its naming is shown in Fig. 3. The blockage ratio of 0.27 is reported to be the optimum blockage for trapezoidal and cylindrical bodies for the stability and strength of vortex shedding and the linearity of St - Re_D relation [7]-[9]. Therefore the blockage ratio 0.27 is selected for all the bodies.

Body B1 is an inverted Trapezoid. Body B2 is a square with the same blockage as that of the trapezoid; however its lateral faces are at 90°. Body B3 is an equilateral triangle, which is chosen to study the effect of after body shape, change in streamwise length and the width of the rear face. Body B4 and B5 follow the geometry of a trapezoid with some part of the rear end chopped off, to study the effect of after body shape. There is considerable improvement in the performance of a cylinder on introduction of a normal slit [2]. In this line, Bodies B6, B7 and B8 have been chosen to study the effect of a normal slit width.

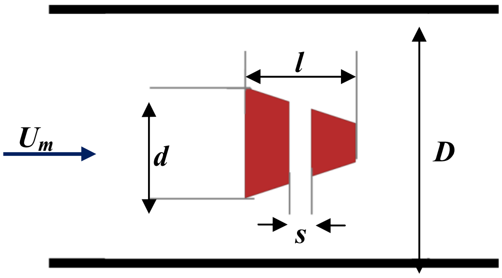
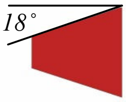
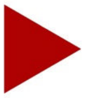
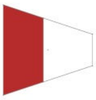
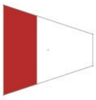
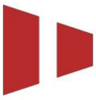
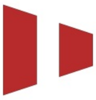


Fig. 3 Geometrical parameters of the bluff bodies

V. RESULTS AND DISCUSSIONS

The wake parameters like Strouhal number, wake width and the vortex formation length were studied for all the bluff bodies. A constancy in Strouhal number and Reynolds number relationship is desirable for a good vortex shedder. The vortex formation length and the wake width provide significant information about the bluff bodies. With the knowledge of wake parameters, one can determine the nature of a bluff body. The trends for the wake parameters were observed and plotted to find out the dependence of these parameters over each other, and to find the effect of the geometry of the bluff body on the wake parameters. This present study also gives a fundamental insight into the vortex formation mechanism with the changes in the geometry and the orientation of the vortex shedder. The supporting images for all the description have been included in the Appendix.

TABLE II
BLUFF BODIES

B1	**$l/d = 1$**	**B2**	**$l/d = 1$**	**B3**	**$l/d = 0.866$**
					
B4	**$l/d = 0.45$**	**B5**	**$l/d = 0.375$**	**B6**	**$s/d = 0.1$**
					
B7	**$s/d = 0.20$**	**B8**	**$s/d = 0.25$**		
					

A. Strouhal Number versus Reynolds Number

In the study of after body effect in bodies B3, B4 and B5, the Strouhal number is observed to increase with the decrease in the streamwise length as shown in Fig. 4. In bodies B6, B7 and B8, on increasing the slit width from 0.1 (B6) to 0.25 (B8), the value of Strouhal number initially increases, attains its maxima, and then falls steeply followed by slow decrease with the increase in the Reynolds number as shown in the Fig. 4. This implies that the introduction of a normal slit initially boosts the shear layer interaction; however after a certain threshold slit width, the bluff body starts acting like a dual bluff body in series, and becomes a hindrance in the shear layer interaction in the wake region. B2 shows the least value of the Strouhal number indicating reduced interaction of the shear layers due to the increased width of the rear face, as expected. Hence, for a trapezoidal body the Strouhal number decreases with the decrease in the streamwise length of the body for the same blockage ratio. This shows that the after body shapes delay the interaction of shear layers. It can be concluded that there exists an optimum normal slit width for trapezoidal bodies for which the shear layer interaction is maximum, which is reflected in the values of Strouhal number. The vortex formation mechanism for each body is shown in the Appendix. For bodies B1 to B5, the images have been shown for $Re_D = 900$ but for B6 to B8, $Re_D = 700$ is shown in the images due to increased diffusion of dye because of shear layer instability.

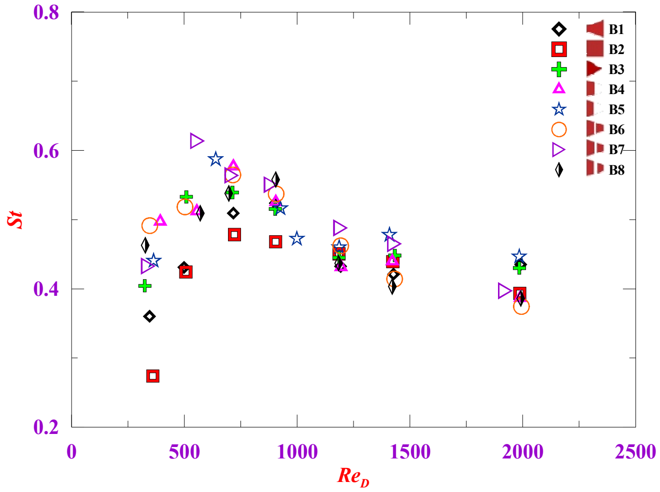
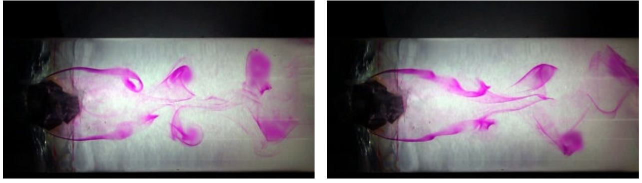


Fig. 4 Variation of Strouhal number with Reynolds number

B. Wake Width and Vortex Formation Length

Non Karman vortex formation cannot be entirely explained on the basis of the shear layer interaction. The shear layers cannot be seen interacting explicitly in most of the blunt shaped bodies. Here the vortices formation takes place without the shear layer interaction and such vortices have been termed as Non Karman vortex. From the experimental observations, many of the bluff bodies exhibited vortex formation that is not entirely Karman; however the shear layers can be clearly seen interacting with each other as shown in Appendix. For such type of vortex formation, the vortex formation length is taken as the point where the shear layers meet. After the flow separation due to the bluff body, the two shear layers from the top and bottom approach each other in the wake and meet at the confluence point to form vortex. This behavior is less dominating at larger Reynolds number where the shear layer instability dominates and leads to increased diffusion of dye.

Another interesting phenomenon observed is the formation of both the alternate and symmetric vortices for the same Reynolds number. Switching of modes from alternate to symmetric and vice versa could be observed, but no periodicity is found. The supporting images are shown in Fig. 5.


Symmetric vortex

Alternate vortex

Fig. 5 Modes of vortex shedding for Body B8 at $Re_D = 900$

Shear layer instability is marked by strong vortices formed in the shear layer itself that grow in size and strength. Shear layer instability is dominant in the blunt shaped bodies, mainly at higher Reynolds number. The vortices formed in the shear layer are observed to be symmetric in nature. Multiple shear vortices shed from the shear layer, roll up to form a single primary vortex and moves further. But the identification of the vortex becomes difficult in such cases. The onset of shear vortex formation in the shear layer is qualitatively found to reduce the vortex formation length. The presence of shear vortices in the two shear layers increases the interaction between the opposite side shear layers, resulting in early formation of vortex. The wake width is observed to become constant after the onset of formation of shear layer vortices. This effect is highly dominant in the bodies B4 and B5, even at low Reynolds number which made the identification of vortex formation length difficult for these bodies, as represented in the figures shown in Appendix.

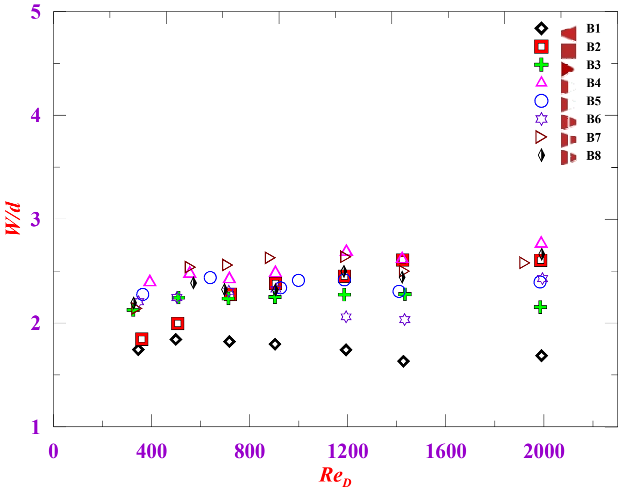


Fig. 6 Variation of wake width with Reynolds number

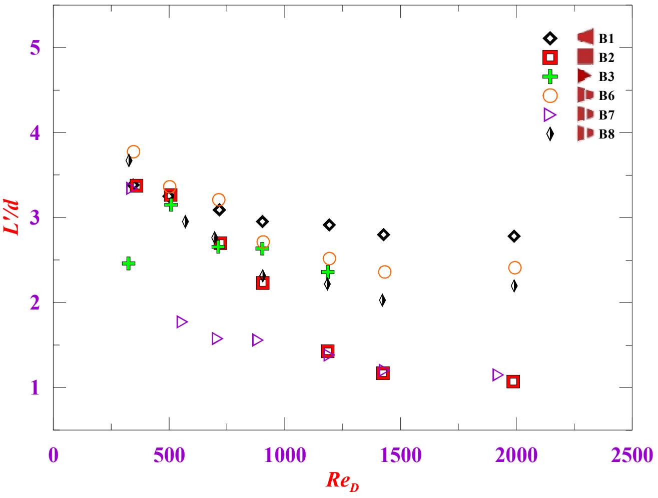


Fig. 7 Variation of vortex formation length with Reynolds number

The study of the after body effect of the trapezoidal bodies reveals that the wake width increases with the decrease in the streamwise length of the trapezoid, which can be observed from the plot shown in Fig. 6. The decrease in the streamwise length is also observed to induce shear layer instability to the vortex formed. The longer is the streamwise length, stable is the shear layer formed. Hence after body shape is found to delay the onset of shear layer instability for a given blockage ratio as shown in Figure 8. Similar to the Strouhal number and the Reynolds number relationship, the wake width also shows a similar behavior. It first increases and then tends to become constant, which indicates a possible relationship that exists between the wake width and the Strouhal Number. The wake width is observed to be tending to become constant with the increase in Reynolds number as shown in Fig. 6. The interaction between the two shear layers depend on the wake width, and the Strouhal number in turn depends on the interaction of the shear layers, thus the nature of curve of Strouhal Number can be explained by the variation of the wake width. The effect of introducing a normal slit passing through the trapezoid's center is studied for the bodies B6, B7 and B8. The introduction of slit in the trapezoid seemed to increase the shear layer interaction. However the vortices formed were not very strong but had a Karman character. Body B7, trapezoid with slit width is observed to have the largest Strouhal number value, one among the least vortex formation length, and possesses the highest wake widths among all. With the increase in the slit width, the wake width increases first, and attains a maximum value and then finally decreases which can be observed from Fig. 6. Similarly, the vortex formation which shows the inverse behavior to the wake width, initially decreases, attains a minimum and then increases again on moving from B6 to B8 as depicted in Fig. 7.

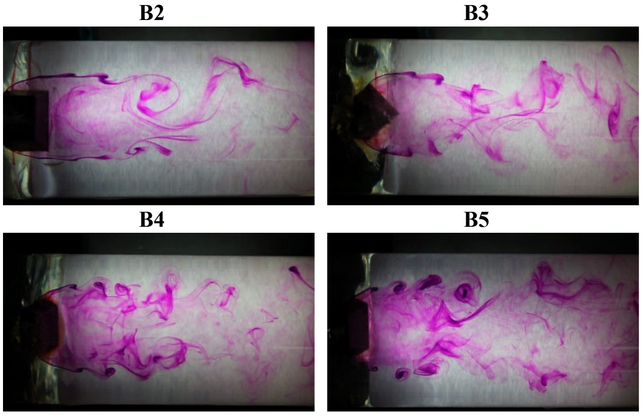


Fig. 8 Increase in shear layer instability with the decrease in the streamwise length from B2 to B5 at $Re_D = 900$ (after body shape effect)

The vortex shedding phenomenon can find potential applications in vortex flowmeters, energy harvesting, heat exchangers, vortex generators etc. For obtaining the best output in an energy harvester or a vortex flow meter from a vortex, the location of placing the sensor is very important. The flow visualization helps us to understand that the sensor should be located at the vortex formation length for a particular body to obtain high amplitude signals. Thus flow visualization helps us in understanding the physics behind the vortex formation mechanism.

VI. CONCLUSIONS

A good vortex Shedder is characterized by good strength and stability of the vortex generated least dependence of Strouhal number on the Reynolds number and minimum power losses. All these parameters depend on the geometry of the vortex shedder. The bluff bodies have been generally studied in two broad divisions; round shaped bodies and the sharp edged bodies. Round shaped bodies, particularly cylinders are found abundantly all around us. It is observed that blunt shaped bodies are generally good vortex shedders, though they result in significant energy losses. Therefore in a search for an optimum body, various flow visualization experiments were performed under laminar flow conditions. Flow visualization helped us to understand the effect of the change of the shape and orientation, introduction of slit and the after body shape effect in a bluff body on the vortex formation mechanism.

Careful observation of the wake parameters of the bluff bodies revealed that the Strouhal number, vortex formation length and the wake width are dependent on each other. The wake width is found to have an opposite behavior to that of the vortex formation length. The wake width determines the degree of shear layer interaction, and hence the Strouhal number.

The experimental investigations on the modification of trapezoid show that there is not much significant effect on Strouhal number, especially at high values of Reynolds number. The introduction of an optimum normal slit in trapezoid improves the shear layer interaction. The decrease in the streamwise length of trapezoidal bodies shows a decrease in the vortex formation length, increased shear layer instability with no significant effect on the wake widths.

The experimental investigations highlight that a trapezoid with normal slit of width 0.2 times the projected width of the body and an inverted trapezoid can be classified as good vortex shedders.

This flow visualization study has given an insight into the various vortex formation mechanisms for laminar flow, and it sheds light on bluff bodies other than the cylinder and the trapezoid, as good vortex shedders, and paves the way for future research on novel unconventional bluff bodies.

APPENDIX

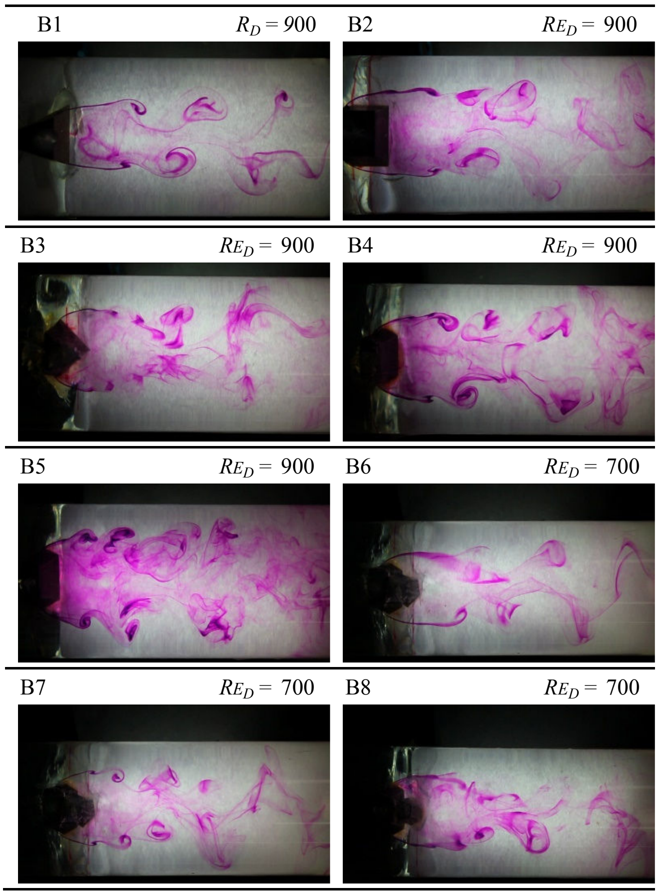


Fig. 9 Vortex formation mechanism for bluff bodies

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REFERENCES

[1] Zdravkovich, M. M. (2003). *Flow around circular cylinders: applications* (Vol. 2). Oxford University Press

[2] Igarashi, T. (1999). Flow resistance and Strouhal number of a vortex shedder in a circular pipe. *JSME International Journal. Series B, fluids and thermal engineering*, *42*(4), 586-595

[3] Gandhi, B. K., Singh, S. N., Seshadri, V., & Singh, J. (2004). Effect of bluff body shape on vortex flow meter performance. *Indian Journal for Engineering and Material Sciences*, *11*, 378-384.

[4] Kamemoto, K., Yokoi, Y., Tanaka. E., 1992 "Observations on the Flow around Circular Cylinder and Trapezoidal Cylinder in a Circular Pipe by Dye - Injection Method." *11th Australasian Fluid Mechanics Conferences University of Tasmania, Hobart, Australia*., 14-18 December, pp. 699 - 702.

[5] Venugopal, A., Agrawal, A., Prabhu, S. V., "Frequency Detection in Vortex Flowmeter for Low Reynolds Number using Piezoelectric Sensor and Installation Effects." Sensors and Actuators A., Vol. 184, pp. 78-85, 2012.

[6] Venugopal, A., Agrawal, A., Prabhu, S. V., "Influence of Blockage and Shape of a Bluff Body on the Performance of Vortex Flowmeter with Wall Pressure Measurement." Measurement, Vol. 44, 2011, pp. 954 – 964.

[7] Venugopal, A., Agrawal, A., & Prabhu, S. V. (2011). Review on vortex flowmeter—Designer perspective. *Sensors and Actuators A: Physical*, *170*(1), 8-23.

[8] Takamoto, M., Terao, Y., (1999) "Standardization of Vortex Shedding Flowmeter." *Proceedings of the 4th International Symposium on Fluid Flow Measurement*, July, Denver, USA.

[9] Venugopal, A., Agrawal, A., Prabhu, S. V., 2010 "Influence of Blockage and Upstream Disturbances on the Performance of a Vortex Flowmeter with a Trapezoidal Bluff Body." *Measurement*, Vol. 43, pp. 603 - 616.

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