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The Laminar Horseshoe Vortex Upstream of a Short-Cylinder Confined in a Channel Formed by a Pair of Parallel Plates

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Abstract : A flow visualization experiment was performed in order to characterize the laminar horseshoe vortex system that appears upstream of the junction of a short cylinder and a pair of flat parallel plates. The experiments were performed in a water tunnel and the technique used for flow visualization was laser illumination of seeded particles whose traces were captured using long exposure photography. Geometrical and flow parameters, such as Reynolds number and height-to-diameter ratio of the cylinders, are varied during the experiments and the flow regimes are analyzed as a function of these parameters. The behavior of vortex systems is reported. For low Reynolds number cases, the vortices stay in a fixed position, as the Reynolds number is increased the number of vortices grows and for larger Reynolds numbers the vortex system becomes oscillatory and for further increases it becomes periodic. As for the dimensionless height of the cylinders, the vortex system is weak for short cylinders and increases its strength and number of vortices as the cylinder height-to-diameter ratio is increased. For further increases in height the vortex system do not change, which shows that the flow becomes independent of the height-to-diameter ratio for sufficiently tall cylinders. Information of the frequency of appearance of periodic vortices is also included.

Keywords : Horseshoe vortex, Channel flow, Short cylinder, Separation effect, Periodic behavior.

1. Introduction

Horseshoe vortex systems are present in many engineering situations, such as the plate-fin and tube juncture of compact heat exchangers, airplane wing-body juncture, near the riverbed of a bridge, or near the base of tall buildings. Because of the deceleration of the flow upstream of the obstacle, the boundary layer over the plate separates and rolls up in front of the cylinder, wraps around it and trails off behind creating a horseshoe-shaped vortex. This horseshoe vortex system is an important feature of the flow and plays a determinant role in the physics of the different situations upon which it appears, such as in increasing the heat transfer coefficient in the neighborhood of heat exchanger surfaces formed by plates and cylinders. An interesting feature of horseshoe vortex flows is that as the parameters, such as Reynolds number and geometry, change, the flow pattern takes on different and unusual forms.

The nature of horseshoe vortex systems has been studied to some extent. Schwind (1962) performed experiments upstream of a wedge mounted over a flat plate and found the presence of horseshoe vortices for these flow conditions. He observed different flow regimes depending on the flow velocities. These regimes started with steady boundary layer separation with no vortices visible for the lowest speeds; as the velocity was increased, a single clockwise rotating (when the flow is seen as coming toward the cylinder from the left) vortex with a small counter-clockwise rotating vortex appeared; for further increases in velocity, the number of vortices increased and vortex oscillations started until they were regularly established, and merging of vortices was seen. A more extensive investigation was carried out by Norman (1972). He studied the flow around cylinders and rectangular boundary layer trips using smoke flow visualization. He examined the configuration of the vortices upstream of the obstacle and proposed models for the steady flow patterns. The horseshoe vortex core was seen to be further away from the wall than on the plane of symmetry and was almost stagnant. He also observed oscillatory behavior within the horseshoe vortex system and observed that the vortex oscillations begin at an almost constant Reynolds number based on obstacle size. Baker (1979) studied experimentally the horseshoe vortex that is formed around the base of a cylinder by a laminar boundary layer that has separated. He used a wind tunnel and smoke visualization, observed vortex oscillations and took velocity measurements. He encountered different flow patterns depending upon the flow speed and cylinder size with more vortices appearing as the flow velocity was increased. Above a certain velocity, the entire horseshoe vortex system became oscillatory in a regular manner. At still higher velocities the flow became unsteady and turbulent. In a more recent paper, Baker (1991) studied the oscillation of laminar horseshoe vortex systems, classifying them into two types: (a) oscillations due to an oscillation of the entire separated flow system upstream of the cylinder and (b) horseshoe vortex oscillations due to an oscillation of the vortex core of the primary vortex. These hypotheses were used to identify how the frequency of oscillation varied and to what parameters this frequency was sensitive. The author found that oscillations of type (b) were first observed and these oscillations triggered the stronger oscillations of type (a).

Additional investigations have been reported by Thomas (1985), who was the first to point out the possible effect of height-to-width ratio on the nature of the horseshoe vortex system, Seal et al. (1995), who studied the vortex system at a rectangular block-flat plate juncture. Chang et al. (2002), who studied the horseshoe vortex system near a vertical plate-base plate juncture. These last authors conducted their experiments in a free-surface water channel and studied the effect of Reynolds number as well as the effect of five different height-to-width ratios. For the flow conditions of their experiments, they recognized four major categories defined as (a) steady vortex system, (b) periodic oscillation vortex system with small displacement, (c) periodic breakaway vortex system, and (d) turbulent-like vortex system.

A paper by Simpson (2001) provides an excellent review of the investigations that had studied juncture flows, both over streamlined and blunt bodies. He reviews the computational methods used to capture the flow features of horseshoe vortex systems. They also review some work on the control, modification, or elimination of such vortices.

Several studies have been recently conducted in relation to the flow over blunt bodies located inside a parallel-plates channel: Scanlon et al. (1999) performed a numerical simulation of the laminar vortex shedding from a rectangular cylinder within a confined channel, Kim et al. (2004) performed a large-eddy numerical simulation of the flow past a square cylinder confined in a channel, Hwang and Yang (2004) performed a numerical study of the vortical structures around a wall-mounted cubic obstacle within a confined channel. These authors studied both the horseshoe vortex system and the laminar wake for low-to-moderate Reynolds numbers, finding that unsteady horseshoe vortex systems are only found in the entrance region of the channel, and hard to find for obstacles located in the fully viscous channel region. Rao et al. (2004) used flow visualization techniques to study the fluid structure between a circular cylinder and an open channel bed, having carried their experiments over smooth and rough beds, concluding that the horseshoe vortex structure affects many of the other flow structures.

Most of the previously reported studies have focused on studying the nature of the horseshoe vortex system under the effect of the Reynolds number and distance from leading edge of the plates, but have not devoted much interest to the effect of height-to-width ratio, especially for the case of the circular cylinder. The case of flow around short cylinders mounted inside a flat plates channel have not been studied sufficiently and may be of interest in applications such as heat exchanger design, and for such a reason the present study concentrates in the analysis of this flow situation. This investigation employs qualitative information obtained by a non-intrusive technique such as seeding of neutrally buoyant particles in order to obtain a picture of the instantaneous velocity field of the domain of interest.

2. Experimental Apparatus and Method

2.1 Test Conditions and Flow Visualization Technique

Qualitative flow visualizations and quantitative measurements were performed for the flow occurring upstream of a short cylinder mounted normal to the surfaces of a channel formed by a pair of flat plates. The experiments were conducted in a water tunnel (model 1520, built by Rolling Hills Research Corporation, El Segundo, CA), installed in the Thermofluids Laboratory of the Universidad Autónoma de San Luis Potosí, México. The test section of the water tunnel is 0.381 m high, 0.508 m wide and 1.5 m long. The bottom and the two sidewalls of the test section have tempered glass windows to allow visual access to the model flow features. The range of velocities that are possible range from 0.02 to 0.3 m/s, and a particular velocity within this range can be selected by varying the pump rotational speed by means of a variable-frequency drive. The downstream end of the delivery plenum of the water tunnel has a section with flow-conditioning elements. The first is a perforated stainless steel plate, which reduces the turbulence to a small scale, followed by a fiberglass screen that further reduces the turbulence level. The last is a honeycomb flow straightener. The contraction section of the water tunnel has an area ratio of 6:1. This geometry provides good velocity distribution turbulence reduction, and avoidance of local separation and vorticity development.

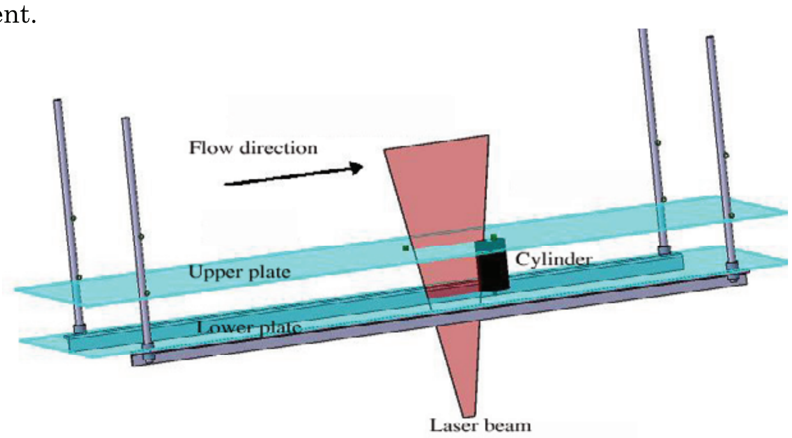


Fig. 1. Schematic of the experimental setup.

Figure 1 shows a schematic of the experimental model and light disposition used in the experiments. The model was suspended inside the test section by attaching it to the frame of the water tunnel. Circular cylinders of constant diameter (D = 0.05 m) were mounted between a pair of horizontal flat plates at a fixed distance from the leading edge (l = 0.75 m). The upper and lower model-plates were made of a 3 mm thick, 1.2 m long transparent acrylic (Plexiglas M) and the cylinders were made of Nylamid. The fluid moves from left to right. In order to reduce perturbations that could affect the development of the boundary layer along the plate, the leading edge was streamlined. To show the effect of the height-to-width ratio of the normal cylinders, several cylinder heights were chosen (ranging from 2 cm to 8 cm). The water was seeded with 14 micron silver-coated hollow glass spheres (manufactured by Potters Inc, Carlstadt, NJ). These glass spheres reflect the light emitted from a 30 mW He-Ne laser tube (manufactured by JDS Uniphase, Santa Rosa, CA) that has been opened into a light sheet by use of a cylindrical lens (manufactured also by JDS

Uniphase). The laser light was cast through the bottom of the water tunnel to illuminate a fan-shaped plane, which serves to keep track of the two-dimensional motion of tracer particles on the vertical plane of symmetry ahead of the cylinder.

A reflex photographic camera with a 50 mm f/2.5 compact macro lens and a black and white photographic film were used to capture the streaks traced by the suspended particles. Exposure times of 1/15 and 1/8 of a second were chosen as the right times for the illumination and velocity conditions of the experiment. The images presented in this paper were digitized after developing the film. Direct observation of the vortex system was also made with the help of video recordings that were later analyzed in detail.

2.2 Experimental Conditions

The diameter, D, was used as the characteristic length for defining the relevant nondimensional parameters for this study. Other geometric dimensions of importance are the separation between plates (and cylinder height), h, and the distance from leading edge of the plate to cylinder center, l. The important flow parameter is the velocity, V. Having defined the characteristic length, the velocities to be tested, and the dimensions of the different cylinders tested, the nondimensional parameters for the experiment are the following: height-to-diameter ratio, $H = h/D$, ranging from 0.4 to 1.6, ratio distance from tube center to leading edge of plate to diameter, $L = l/D$, equal to 15, tube diameter based Reynolds number, $Re = VD/\nu$ (where ν is the kinematic viscosity of the fluid), ranging from 1500 to 5500.

The experiments were conducted by fixing the position of a cylinder of a given diameter and height and increasing the speed within the established range of Reynolds number values. We started with the shortest cylinder ($H = 0.4$) and proceeded with taller cylinders with increases of height until we ended up with the tallest cylinder ($H = 1.6$). We studied the effect that Reynolds number and cylinder height have on the nature of the vortex system upstream of the cylinder. Frequency response of vortex systems was expressed in terms of Strouhal numbers, $St = \omega D/V$, where ω is the frequency of appearance of vortices. A detailed description of the results will be given in the next section.

3. Results

3.1 Experimental Validation

The results were validated by repeating part of the experiments performed by Baker (1979). An experiment especially used for validation was that of a single cylinder mounted over a flat plate. To this end, a cylinder with $H = 0.5$ was located at positions from the leading edge expressed by the cylinder diameter-to-thickness of boundary layer ratio at that position, D/t, where t is the boundary layer thickness ($\delta_{99\%}$), and the nature of the vortex system was observed. Four different cases were observed within the range tested: steady systems with two, four and six vortices, and unsteady vortex systems. Figure 2 shows a comparison of the results of this validation experiment and the map of behavior reported by Baker (1979). Very good agreement is observed between our experiment and that of Baker (1979).

3.2 Flow Visualization

We determined whether the cylinder was located inside the entrance flow region or in channel flow region; by using Sparrow integral solution entry length we found that the cylinder was located within the entrance flow region for all cases. Four different flow regimes were observed for the range of Reynolds numbers and parameter H described in Subsection 2.2. These flow regime are (i) steady vortex systems with variation of the number of vortices present, (ii) oscillatory vortex system, (iii) amalgamating vortex system and (iv) breakaway vortex system. In some situations, a transition between two systems is also observable. Figure 3 shows the values of Reynolds number and H at which each flow regime appears. It can be seen that the region of low Reynolds number and small H is where steady systems appear. By comparison with results for tall cylinders with a single plate, presented by Pérez-Gutiérrez et al. (2006), the stabilizing effect of the second plate is evident, especially as the two plates get closer together. Next to the region of steady vortices, for small increases of Reynolds number or H, there is a narrow region of oscillatory vortices that later gives place to amalgamating vortex systems, which for the larger Reynolds numbers and H values are followed by breakaway vortex systems.

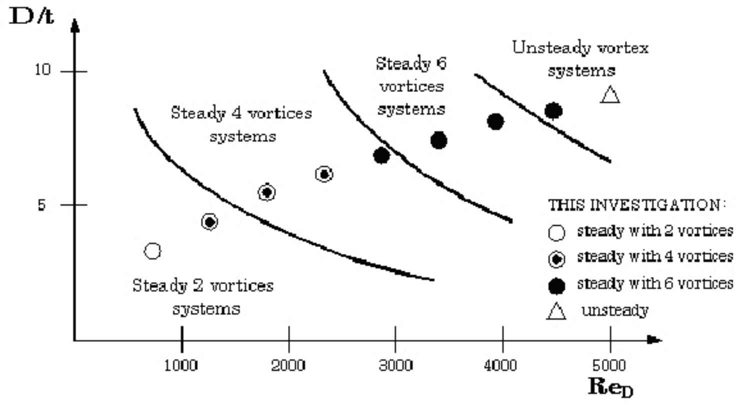


Fig. 2. Results obtained by the validation experiments plotted in the map of behavior reported by Baker (1979).

Fig. 3. Appearance of vortex systems as a function of height-to-diameter ratio and Reynolds number for L/D = 15. O = steady vortex systems, ~ = oscillatory systems, □ = amalgamating systems, Δ = breakaway systems. The overwriting of symbols implies points where there is a transition of two regimes with features of both systems being present.

In all vortex systems studied there are vortices over each plate forming the channel. There are main vortices, which start with the vortex nearest to the cylinder, and are identified in the pictures with natural numbers starting with 1, where number 1 corresponds to the vortex nearest to the cylinder, and secondary vortices, which alternate between main vortices and rotate in the opposite sense and are located between pairs of consecutive main vortices, designated with primed natural numbers, where vortex 1' is the vortex nearer to the cylinder, next to vortex 1. In a system of vortices, the vortex rotational speed and size decrease for vortices farther away from the cylinder.

Steady vortex systems are the first to appear and are formed by one or more vortices, with the center of rotation of each fixed in space. Three different cases of steady vortex systems are shown in Figs. 4, 5 and 6, where the height-to-diameter parameter is fixed but the Reynolds number is increased. It can be seen from the figures that neither the position of vortex 1 does seem to change with respect to the cylinder nor its size as the Reynolds number is increased, but the number of vortices in each system increases as the Reynolds number grows. In the other sense, by maintaining the Reynolds number fixed but increasing the height-to-diameter ratio, the vortex system moves away from the cylinder, and the number of vortices increases.

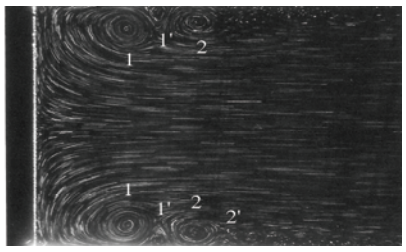


Fig. 4. Steady vortex system for H = 0.8, L = 15, Re = 1523. Main flow is from right to left.

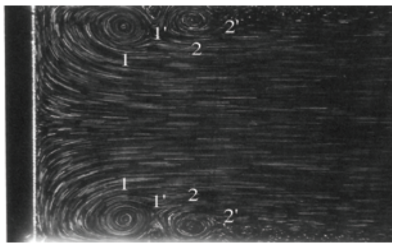


Fig. 5. Steady vortex system for H = 0.8, L = 15, Re = 2093. Main flow is from right to left.

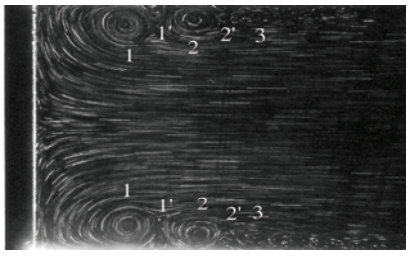


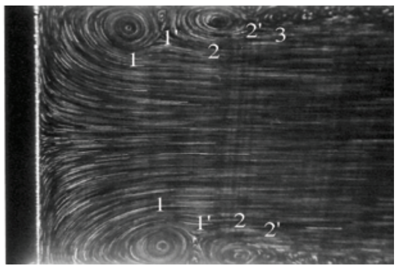
Fig. 6. Steady vortex system for H = 0.8, L = 15, Re = 2663. Main flow is from right to left.

Oscillatory systems occur next to steady systems, the brief range of appearance of these vortex systems suggests that they are transitional systems between steady and amalgamating systems. In these systems the vortex center begins to oscillate, in general vortex 2 moves toward vortex 1, giving place to an oscillatory motion, where the size of vortex 1' decreases or grows depending on whether vortices 1 and 2 get closer or farther apart. The intensity of vortex 2 may cause i) a slight oscillation in vortex 1, which is the behavior that usually presents immediately after the system loses its steadiness because of slight increases of Reynolds number or H, ii) collisions with vortex 1 where vortex 2 may disappear, and iii) a behavior with some of the features of an amalgamating vortex systems, where vortex 2 tries to capture vortex 1, but due to the strength and size of vortex 1, this does not disappear and causes vortex 2 to disintegrate and to be replaced by a new vortex that is born in the same place where used to be the old vortex 2.

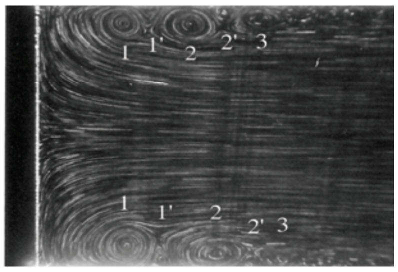
An oscillatory system with a tendency to amalgamate is shown in Fig. 7, which shows the vortex locations for different stages of the period, $T = 1/\omega$. The systems of vortices of the upper and lower plates are not in phase, but do have the same frequency. Figures 7(a) and (b) show a process in which vortices 1 and 2 get closer together because of motion of vortex 2 toward the cylinder, this weakens vortices 1 and 2. In Fig. 7(c) vortices 1 and 2 reduce their strength to their lowest value, and vortex 2 begins to move back to its initial position. In Fig. 7(d) both vortices have moved away from each other and have recovered their strength.

Amalgamating vortex systems are periodic systems where the vortices first appear in the boundary layer separation region with a very elliptic shape, and acquire a circular shape as they get closer to the cylinder. This vortex reaches its larger size in the middle of its trajectory and begins to shrink as it get closer to the cylinder. When it gets closer to the cylinder, it starts a back motion and collapses with vortex 2. The photographs of Fig. 8 show clearly the process of creation and destruction of a vortex of this kind, the vortex that is followed is identified with an asterisk.

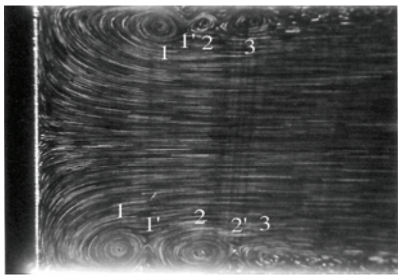
In Fig. 8(a) it is possible to see the moment when the vortex is being created, having initially an elliptic shape, keeps growing up to the moment shown in Fig. 8(b). In Fig. 8(c) the vortex is about to merge with the vortex that appeared the previous cycle, and in Fig. 8(d) has swallowed it. It keeps its motion toward the cylinder. In Fig. 8(f) the vortex is closest to the cylinder and has reduced its size. In Fig. 8(g) the vortex is in the end of the movement backwards and in Fig. 8(h) has been swallowed by the vortex that was born one period later.



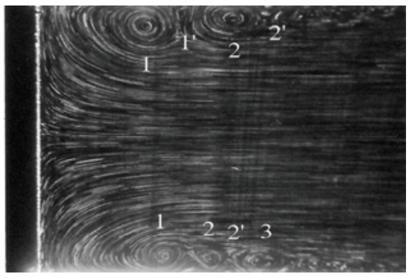
(a) t/T = 1/8



(b) t/T = 1/2

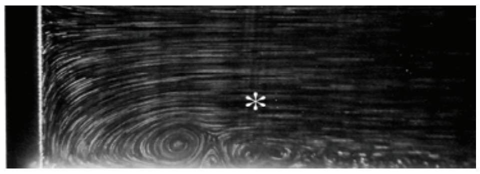


(c) t/T = 5/8

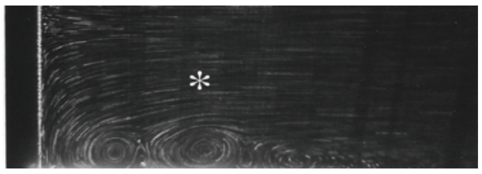


(d) t/T = 7/8

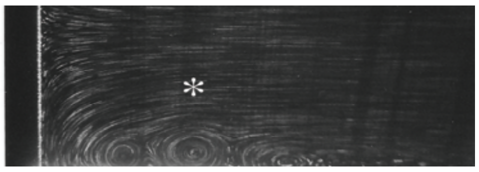
Fig. 7. Sequence of photographs that illustrate the behavior of an oscillatory system with a tendency to amalgamate for H = 0.8, L = 15, Re = 3233. Main flow is from right to left.



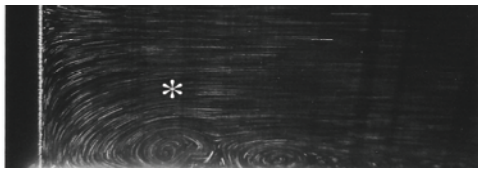
(a) t/T = 1/12



(b) t/T = 1/4

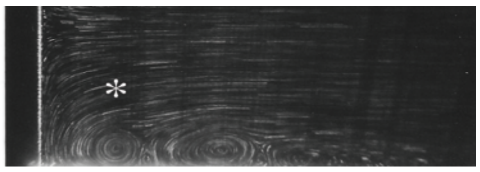


(c) t/T =1/3

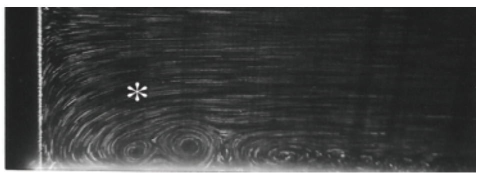


(d) t/T = 5/12

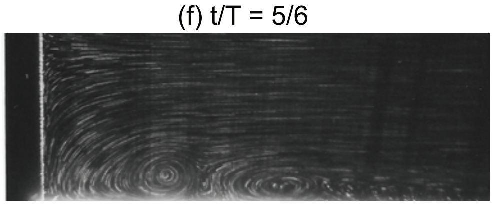
(e) t/T = 2/3



(f) t/T = 5/6



(g) t/T = 11/12

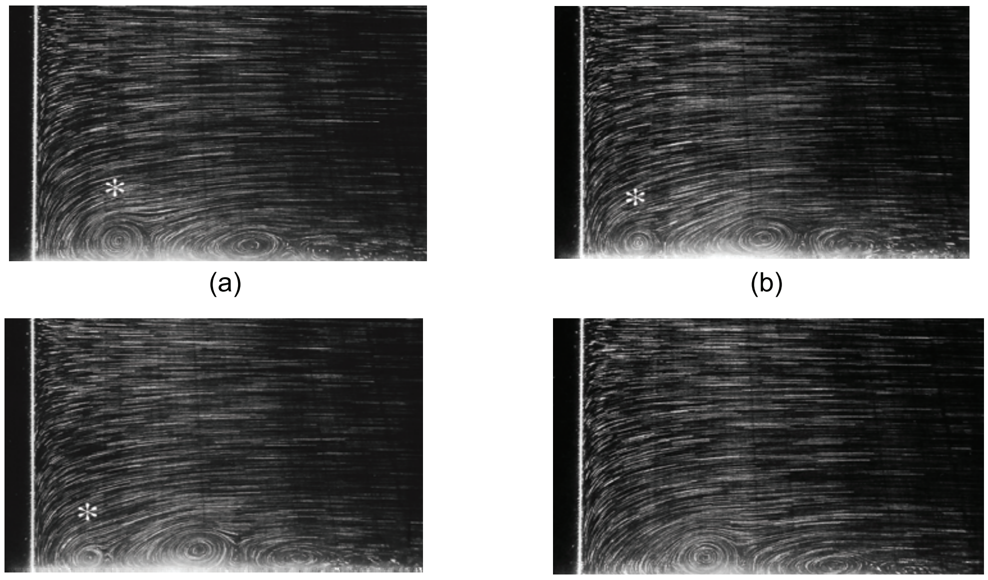


(h) t/T = 1

Fig. 8. Sequence of photographs showing the lifecycle of an amalgamating vortex. L = 15, H = 0.8, Re = 3803. Main flow is from right to left.

For increases of Reynolds number, the vortices of amalgamating systems approach closer to the cylinder, their size is reduced and their motion backwards is reduced. For the case of a constant Reynolds number, as H is increased, vortex 1 approaches closer to the base of the cylinder, and its maximum diameter tends to decrease and it becomes almost constant for values of H = 1.4 and up.

When the motion backwards of vortex 1 is negligible, the vortex system may be considered as a breakaway vortex system. In these kinds of systems, vortex 1 disappears near the base of the cylinder instead of being swallowed by the next vortex. In general, the form in which the vortices are created is the same as in amalgamating vortex systems. Figure 9 shows a sequence of photographs that illustrate the way vortices disappear in breakaway vortex systems.



(a) (b) (c) (d)

Fig. 9. Sequence of photographs showing the way vortices disappear in breakaway vortex systems. L = 15, H = 1.4, Re = 3803. Main flow is from right to left.

3.3 Periodic Behavior

Oscillatory, amalgamating and breakaway vortex systems are periodic systems with varying frequency of appearance of vortices, which increases as the velocity of the flow grows. Figure 10 shows the relation between Reynolds number, height-to-diameter ratio H, and dimensionless frequency of appearance of vortices. As it can be seen from the figure, the dimensionless frequency (expressed by the Strouhal number, St) increases monotonically with the Reynolds number. This can be explained by the fact that as the Reynolds number is increased so is the flow velocity, and with it the acceleration due to drag that the vortex structure suffers. For the case of H lower than 1.0, the parameter H seems to have the effect of decreasing the frequency of appearance of the vortices. This may be due to the reduction of size of the vortices as H is reduced, which reduces the mass of the vortical structures and makes the vortices easier to accelerate by the main flow, or due to the steeper velocity gradients in which the vortices are immersed that sweeps them with higher strength. For values of Reynolds number and H greater than 3250 and 1.0, respectively, the system experiences a periodic behavior which seems to be only a function of Reynolds number, independently of the value of H and the kind of system that appears in each case. This indicates that for H greater than 1.0, the vortex structures over each plate forming the channel become independent of each other, and further increases of H do not have an effect on the frequency of appearance of periodic vortices.

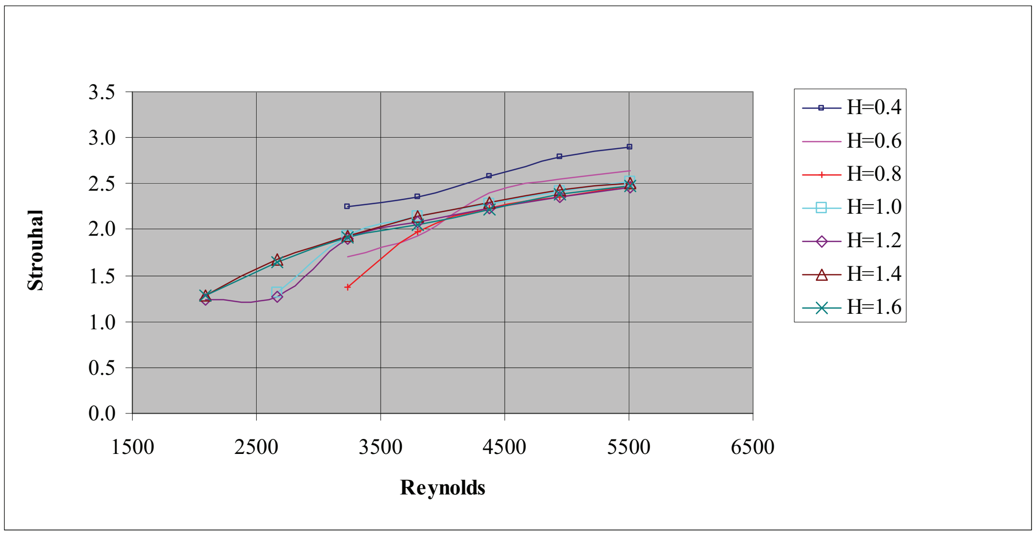


Fig. 10. Dimensionless frequency of appearance of periodic vortices as a function of Reynolds number and dimensionless plate separation.

4. Conclusion

The height-to-diameter ratio as well as flow conditions have an important effect in the behavior of vortex systems for the configuration studied in this paper. Four different flow regimes were observed in the flow: steady, oscillatory, amalgamating and breakaway vortex systems, although combinations of some of these were also observed in the parametric border region of some systems, like the case of periodic vortex systems with a tendency to amalgamate. By comparing the flow features in the channel with results of other investigations that study tall cylinders mounted over a flat plate, it is observed that the height-to-diameter parameter has a stabilizing effect over the flow, displacing the appearance of periodic systems to higher values of Reynolds number. The frequency of appearance of periodic vortices was also studied, monotonic growth of the dimensionless frequency was observed as the Reynolds number was increased. From the plot showing the variation of the frequency of appearance of periodic vortices versus Reynolds number and H, it was also possible to determine the value of H at which the vortex structures over each plate become independent of the parameter H. Independent behavior occurred for values of H greater than 1.0.

Acknowledgments

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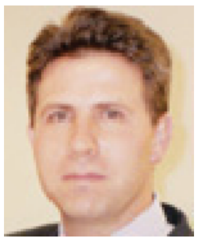

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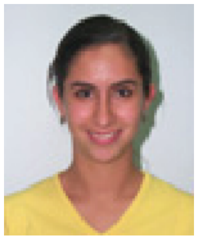

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