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A VISUAL INVESTIGATION OF A CYLINDER WAKE FLOW ABOUT A DOWNSTREAM PERPENDICULAR CYLINDER

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ABSTRACT

The interaction between a circular cylinder and an incoming wake from a perpendicular upstream cylinder has been investigated using flow visualization techniques to gain physical insight into the flow mechanism. The region of interest is near the stagnation region of the downstream cylinder where the interaction leads to a system of necklace or horseshoe vortices "wrapped" around the downstream cylinder and extending downstream. Five flow regimes are observed. These regimes depend on the separation between the cylinders. They can be steady or unsteady within the Reynolds number range studied. The characteristics of each of the regimes are presented.

INTRODUCTION

Three dimensional flow patterns arising from the interaction between an upstream cylinder wake and a perpendicular downstream cylinder appear in many engineering applications such as building structures, heat exchangers, turbulence generators and can also result from the interaction between hydrogen bubble wire and smoke wire wakes and downstream bodies in flow visualization. The presence of horseshoe vortices at the stagnation region of the downstream cylinder has been studied by many investigators, among them Nagib[1] and Fox *et al*[2-5]. They observed flow patterns that agree closely with some of the authors' findings. However some differences are also evident and these are discussed below.

To explain the creation of these vortices, the vortex-amplification theory was proposed by Sutera *et al*[6-7] and later extended by Sadeh *et al*[8]. This theory suggests that the stretching of cross-vortex filaments amplifies the intensity of vorticity locally. As vorticity in the upstream cylinder wake is transported towards the downstream cylinder, two mechanisms contribute to the resulting vorticity intensity field at the stagnation region of the downstream cylinder. These are the viscous dissipation and the amplification due to stretching of the vortex filaments. A neutral scale exists for the vorticity transported by the stagnation flow such that there is no net amplification or dissipation. Vorticity of smaller scale to the neutral scale dissipates while larger-scale vorticity undergoes net amplification. Visualization studies by Sadeh *et al.*[9-11], have given some early insight into the structure of the vortices in the stagnation region. In these experiments, vorticity was introduced to the free stream by means of an upstream turbulence grid consisting of regularly spaced cylinders perpendicular to both the free stream flow direction and the downstream cylinder, i.e. parallel to the z-axis. They observed a regular array of counter rotating horseshoe vortex pairs distributed spanwise along the downstream cylinder, each pair corresponding to a cylinder within the upstream grid. These studies were limited to a narrow range of conditions and, as shown by the work presented below, did not reveal the full range of flow behaviors and transition conditions.

The purpose of the present paper is to report on a series of hitherto unknown flow regimes in the cylinder-wake interaction.

EXPERIMENTAL METHOD

The experiments were performed in a closed-return water channel at the University of Adelaide. The flow setup and coordinate system are as shown in figure 1. The working section is 100 mm wide x 180 mm high x 500 mm long. A 0.5 mm diameter wire was used as the upstream cylinder rod and a 34 mm outer diameter PVC pipe was used as the downstream cylinder. End plates were placed on the downstream cylinder to help maintain symmetry and to isolate the test region from the side wall boundary layers. The centre-to-centre separation distance L between the cylinders was adjustable. The experiments were conducted at free stream velocities of 93.5, 100 and 106 mm/s, corresponding to Reynolds numbers, based on the upstream cylinder diameter (Re_d), of 47, 50 and 53 respectively. Visualization was achieved by means of hydrogen bubbles produced by a 25μ diameter bubble wire 150 mm (center-to-center distance) upstream from and in the same horizontal plane as the downstream cylinder. A high resolution monochrome video camera was used to capture the images that were recorded using a Hi-8 video recorder. Horseshoe vortex shedding frequency measurements were made by analyzing the video images frame-by-frame.

FLOW VISUALISATION RESULTS

Figures 2(a) to 2(f) show the progression of the regimes as separation distance L/d is increased at a Reynolds number of 47. All visualization images presented in this paper are x-y plane images and on the same z-level as the downstream cylinder axis. Five flow regimes can be identified. These regimes will be referred to as regimes 1, 2a, 2b, 3 and 4. As will be seen later in this section, the numbering of the regimes increases progressively with increasing distance between the cylinders.

Regime 1 consists of a single pair of horseshoe vortices as shown in figure 2(a) for Re = 47 and L/d = 47. At this Reynolds number, Regime 1 occurs at separation

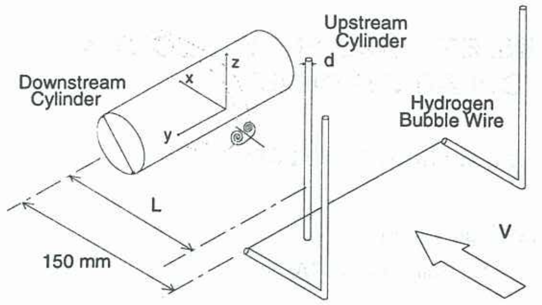


Figure 1: Experimental setup. d=0.5mm, D=34mm, Re_d=47, 50 and 53.

distance 0 < L/d < 48.5. The vortex pair is symmetrical about the x-z plane, hence the counter-rotating vortices appear to be of the same strength (in the sense that they are of the same size and distance from the downstream cylinder). This regime was also observed by Fox *et al.*[2-4]

As the separation distance L is increased the pattern becomes unsteady and more complicated. Two modes of unsteady flow, denoted as regimes 2a and 2b have been identified.

Regime 2a starts at L/d = 49. Figures 3(a-h) show this regime at Re = 47 and L/d = 57. Regime 2a consists of one or more pairs of horseshoe vortices at any instant in time. In this regime, vortices progressively move in a regular fashion towards the downstream cylinder. New horseshoe vortex pairs are created at the upstream cylinder as the two vortex pairs nearest to the downstream cylinder coalesce to form a single, stronger pair. This is a highly periodic process, the frequency of which increases as the gap increases.

The features of regime 2b are comparable to those of regime 2a. The only difference, apart from a difference in the frequencies, is the position of the leading saddle point. Here, the leading saddle point refers to the saddle point ahead of the first vortex pair. In regime 2a, it can be seen that the back flow extends upstream to the leading saddle point (stagnation point) at the rear of the upstream cylinder. In regime 2b, the back flow ends at the leading saddle point some distance downstream from the upstream cylinder, and hence it does not reach the upstream cylinder. It was found that in regime 2b, the coalescence frequency decreases as the gap increases, contrary to the behavior of that in regime 2a.

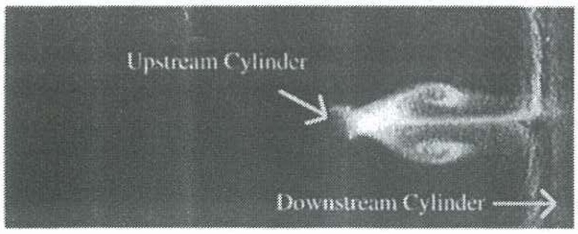
Regime 3 consists of steady (i.e. not coalescing or shedding) pairs of horseshoe vortices in a staggered pattern as shown in figures 2(d-f). They may be caused to shed and coalesce intermittently by deliberately introduced disturbances in the flow. The pattern is dominated by the downstream pair which is not symmetrical (about the x-z plane); the vortices in one pair are of different sizes and the pairs are skewed at an angle. The pattern may switch to its mirror image after it has been caused to shed. The pair nearest to the downstream cylinder is much larger than the pair in front of it, as can be seen in figure 2(d). The number of horseshoe vortex pairs in this system is somewhat uncertain, but as can be seen in figure 2(d), there are at least two. As the gap distance is increased further, only one pair of horseshoe vortices can be viewed clearly, as shown in figure 2(e). The asymmetry and size of the horseshoe vortex pair also decreases as the gap distance increases. This is shown in the sequence of figures 2(d-f). As the gap distance is further increased, the horseshoe vortex pair decreases in size progressively until the vortices can no longer be seen. It is not known whether the vortices no longer exist in this range or whether the size of the vortices is too small to be detected by means of hydrogen bubble visualization. The regime where no horseshoe vortex system appears is noted as regime 4. Nagib[1], who studied regime 3, presented an empirical correlation of the transition condition from regime 3 to regime 4. However, he did not discuss the means by which he detected the transition point.

DISCUSSION

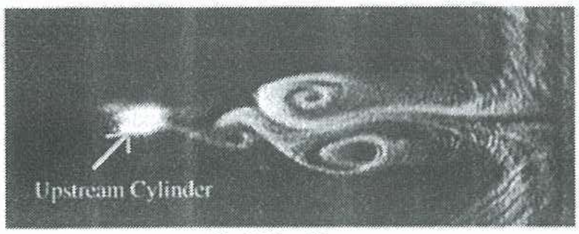
Similar flow patterns to regimes 2a and 2b were documented by Fox[3-4] for a d/D value of 1 and at Reynolds number of $1x10^4$. He varied the separation distance from L/d=1 to L/d=5 (c.f. present experiments where 46 < L/d <.600 Fox only observed two pairs of horseshoe vortices which he reported as shedding. He found that the shedding frequency was lower than the von Karman frequency for a single cylinder as the vortices start to shed. He then found experimentally that the shedding frequency increases, converging towards the single cylinder shedding frequency, as the gap distance increases. The present study reveals a different behavior, which may be accounted for by the fact that the Reynolds number range and the cylinder diameter ratios (d/D) are different from those used by Fox. Figure 4 shows the Strouhal numbers for three different Reynolds number values in the present study. Here, the Strouhal number (*fd/V*)is based on the frequency of coalescence, the upstream cylinder diameter and the free stream velocity. The horseshoe vortices start to become unsteady and coalesce at L/d=48.5, which is the starting point of regime 2a. The coalescing frequency then increases to a maximum point at L/d=59 (a value for of around 8% of a single cylinder Strouhal number value), where regime 2b begins, and then the frequency decreases to zero as L/d increases to 68, where regime 3 begins.

In regime 3, a vortex in a vortex pair seems to differ in size from it's corresponding counter-rotating partner and the vortex pairs are skewed so that the individual vortices forming the pair reside at different distances from the downstream cylinder. Consideration of the local mean velocity field suggests that the vortex closer to the cylinder resides in a lower-streamwise-velocity region than does its upstream partner. This suggests that the circulation of the vortices are different, or that the vortex cores are substantially different in size. Recognizing that the upstream velocity is uniform and the wake produced by the upstream cylinder is likely to be symmetrical, the authors favor the latter explanation for the observed asymmetry. Furthermore, as the gap is increased between the two perpendicular cylinders, the vortex pairs become more symmetrical suggesting that the magnitudes of the opposing circulations are the same.

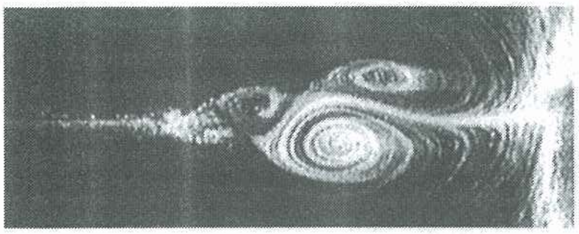
It is important to note that the diminishing size of the horseshoe vortices and the eventual disappearance of the vortices altogether does not preclude the possibility of significant vorticity being present in the stagnation region of the downstream cylinder. However, as the horseshoe vortex length scales decrease, the effects of dissipation become increasingly significant with respect to the amplification in the stagnation region. This can be related to the existence of the neutral scale pointed out by Sutera *et al*[6-7] for which amplification by stretching



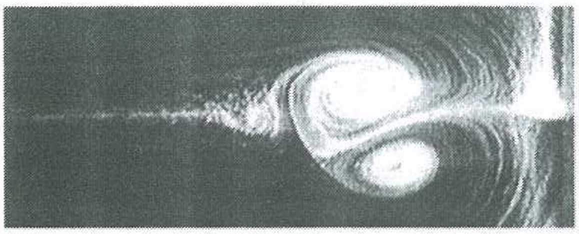
(a) L/d=47



(b): L/d = 53

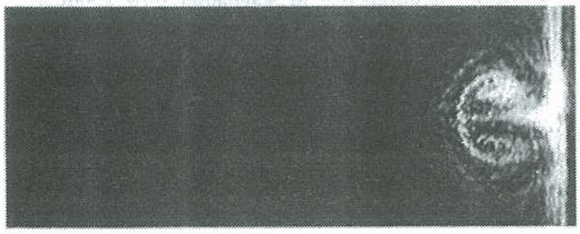


(c): L/d = 65



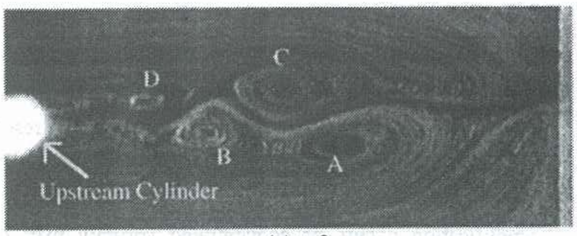
(d): L/d = 75

(e): L/d = 215

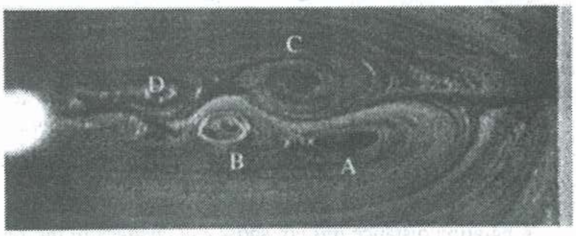


(f): L/d = 535

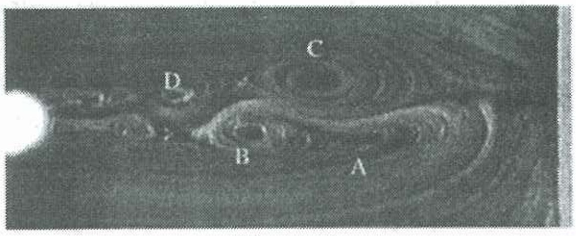
Figures 2(a)-(f): x-y plane images of different regimes as separation distance L/d is increased. (a): Regime 1. (b): Regime 2a. (c): Regime 2b. (d)-(f): Regime 3. Flow is from left to right at Re=47. The downstream cylinder surface lies along the right-hand edge of each image. Regime 4 (not shown) has no visible vortices.



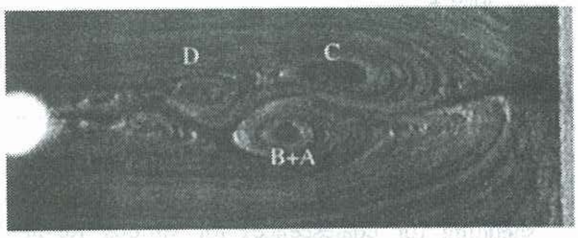
(a) t=0s



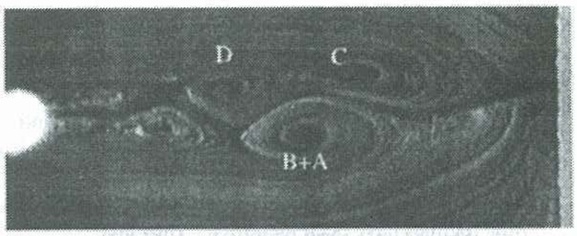
(b): t = 0.12 s



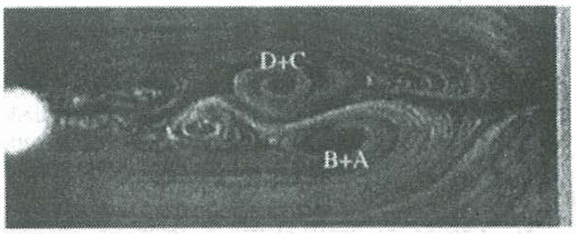
(c): t = 0.24 s



(d): t = 0.4 s



(e): t = 0.52 s



(f): t = 0.76 s

Figures 3(a)-(f): x-y plane images of Regime 2a. In Regime 2a, downstream vortices coalesce as new vortices are created at the upstream cylinder. The process of vortex coalescence can be seen here by monitoring vortex A and B(or C and D) combine and immerge into one. Flow is from left to right at Re=47, L/d=57. The downstream cylinder surface lies along the right-hand edge of each image. Note, due to refractive effects, the upstream cylinder appears larger than in reality.

would be balanced by viscous dissipation with the result that the neutral-scale vorticity would approach the stagnation region of the downstream cylinder with unvarying intensity. It could also be possible that amplification occurs or concentrated vorticity may be present, but this vorticity would be insufficient to cause a velocity reversal and, hence, for the vortices to appear in the flow visualization.

The authors are also aware of the possibility that the bubble wire would effect the flow. However, it is believed that this is unlikely. The corresponding Reynolds number of bubble wire is around 2 to 3 which suggests that the free stream may only be affected mildly by the bubble wire's presence. Changing the bubble wire separation distance did not show any changes in the flow patterns. If the bubble wire wake were to produce any flow instabilities, the separation changes would manifest changes in the flow pattern behavior.

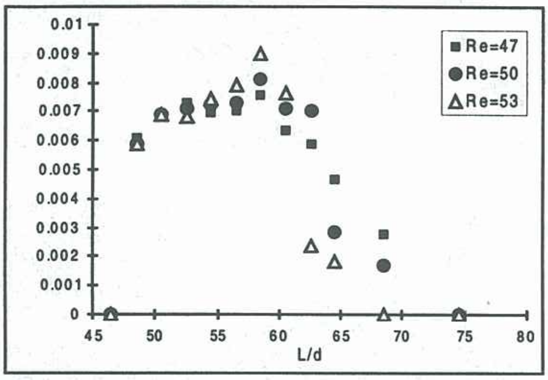


Figure 4: Variation of Strouhal number of vortex shedding (or coalescence) for various Reynolds number base on upstream cylinder diameter.

CONCLUSION

The interaction between a circular cylinder and an incoming perpendicular cylinder wake has been investigated using flow visualization techniques with upstream cylinder Reynolds numbers around 50. Five flow regimes have been identified. They are:

a) Regime 1: Stable, symmetrical horseshoe vortex pair.
b) Regime 2a: A system of horseshoe vortex pairs with a "vortex-street-like" pattern. Neighboring vortices of the same sign coalesce at a regular frequency. Back flow stagnates at upstream cylinder. Coalescence frequency increases as the separation distance increases to a maximum of 8% of the Karman shedding frequency.
c) Regime 2b: Similar pattern to regime 2a. Back flow does not reach upstream cylinder. Coalescence frequency decreases as separation distance increases.
d) Regime 3: Stable, skewed horseshoe vortex pairs, progressing to a stable symmetrical vortex pair at large L/d.
e) Regime 4 : No horseshoe vortex pairs are observed.

The regimes change as the gap distance increases. The Strouhal number range in regimes 2a and 2b is from 0.009 to zero.

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