TECHNICAL NOTE

Flow visualization at the center of a cross composed of tubes

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This technical note presents the results of a visualization study performed in a water tunnel facility to investigate the fluid motion at the center of two tubes arranged perpendicular to each other in the geometry of a cross. The experiments were carried out at a Reynolds number of 1×10^4 (based on the tube diameter and freestream velocity), with tube spacings of up to five diameters between axes. These experiments complement a wind tunnel study previously performed by the author.

Keywords: flow visualization; cross composed of tubes; wake

Introduction

Details of the fluid motion at the center of a cross composed of two tubes perpendicular to each other were published recently in this journal by Fox and Toy.[1] The nature of the flow regimes associated with the geometry were deduced from measurements of surface pressure and fluid velocity made in a wind tunnel at a Reynolds number of $Re = 2 \times 10^4$ (based on the tube diameter and freestream velocity). Fox and Toy[1] showed that two fundamental regimes are possible and that these are dependent upon the spacing of the tubes. In this respect, if the distance between the axis of each tube is less than three diameters, two recirculation cells form in the wake of the upstream tube at the center of the configuration. At spacings beyond this critical value, periodic vortex shedding in the direction of the freestream occurs at the same location.

Fox and Toy[1] found that both of these regimes cause a considerable disturbance at the surface of the downstream tube, the spanwise extent of which is confined to a region within two and one-half diameters of the centerline. They further suggested that this disturbance may lead to enhanced heat transfer rates at the surface of the tube, as is the case when similar regimes occur between parallel tubes (Kostic and Oka[2]).

This technical note provides additional details of the spacing-related regimes at the center of the configuration and of the associated interference effects at the downstream tube. It presents the results of a flow visualization study performed at a comparable Reynolds number.

Experimental details

The experiments were carried out in a low-speed, closed-circuit water tunnel driven by a variable-speed axial flow propeller. The tunnel has a 1.63-m long working section, 331.5 mm in diameter, and produces a uniform velocity profile at the model testing station with a turbulence intensity of less than 1%.

A pair of smooth, polished brass tubes of 16 mm diameter formed the cross geometry illustrated in Figure 1. Each tube completely spanned the tunnel's working section, with an aspect ratio between fixed ends of 21 and an associated area blockage of 6%. The vertical tube could be displaced in the direction of flow to produce a gap at the center of the configuration. The distance between the axis of each tube was denoted L.

Flow visualization was achieved by the injection of dye through 0.5-mm-diameter holes drilled in a fixed configuration on the horizontal model's surface at the center of the span. A permanent record was obtained by photography using studio lighting and Kodak 400ASA Tri-X pan black and white print film.

Discussion of results

All of the experiments were carried out at a Reynolds number of $Re = 1 \times 10^4$, which is in the upper subcritical range for a single tube (or circular cylinder), and are therefore compatible with the tests performed by Fox and Toy.[1] Observations were made over a range of tube spacings from members in contact, $L = 1D$, to a distance between axes of five diameters, $L = 5D$.

Photographs of the spacing-related flow regimes that occur in the wake of the upstream tube at the center of the configuration are presented in Figure 2, together with a picture of the regime at the centerline of a single tube in the same test rig. When the members are in contact, Figure 2(a), the two symmetrically

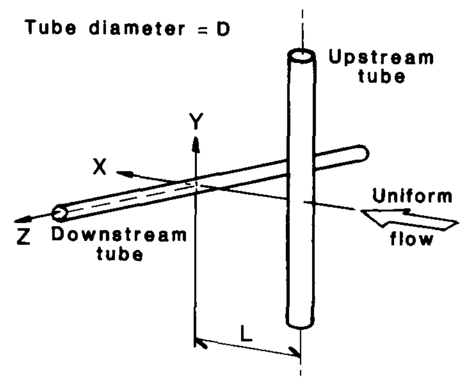

Figure 1 Model geometry and coordinate system

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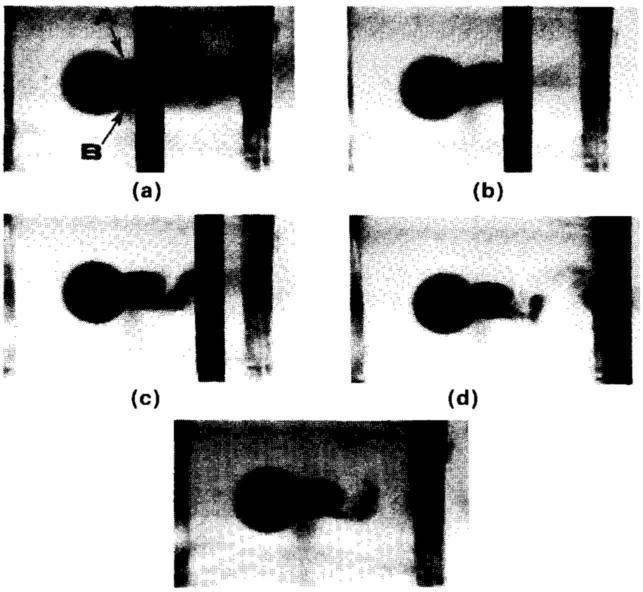

Figure 2 Photographs of the wake of the upstream tube at the center of the cross: (a) tubes in contact, $L=1D$; (b) $L=2D$; (c) $L=3D$; (d) $L=5D$; (e) single tube. (Freestream flow is from left to right, and the Y-direction is perpendicular to the page.)

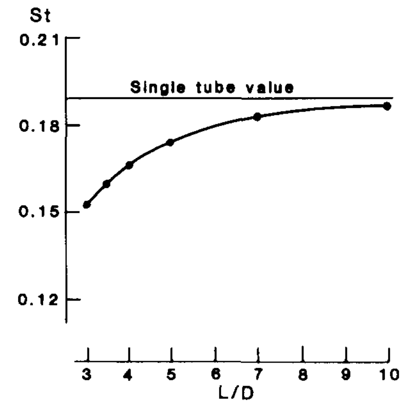

Figure 3 Variation of the Strouhal number, St, of vortex shedding in the gap ($Y=0D$) between the tubes for spacings in the range $3 \leq L/D \leq 10$, as recorded by Fox[5] at a Reynolds number of $Re=2\times10^4$

positioned recirculation "bubbles" identified in the pressure measurements of Fox and Toy[1] are discernible adjacent to the surface of the upstream tube (marked by arrows A and B). Each of these bubbles formed an arch in the spanwise direction and fed a trailing vortex on either side of the point of contact (giving a total of four trailing vortices in the wake). Such a mechanism has also been observed by Zdravkovich[3] in oil-film surface flow visualization experiments performed on a similar model.

As the distance between the two tubes is increased, a pair of recirculation "cells" becomes established in the gap created at the center of the geometry. Figure 2(b) shows the cells associated with a tube spacing of $L=2D$. It corroborates the findings of Fox and Toy[1] with regard to general cell size, in that the overall extent of the recirculation is confined to a region of approximately $|Z|<0.7D$.

The second flow regime in the gap commences at an axis spacing of three diameters, when the downstream tube is no longer positioned in the vortex formation region of the upstream tube. (Bloor[4] determined the extent of the formation region to be $2.5D$ downstream of the axis of a circular cylinder at a comparable Reynolds number.) At this spacing, periodic vortex shedding occurs between the two tubes, as shown in Figure 2(c). The periodicity in the shedding process becomes clearer at a spacing of $L=5D$, Figure 2(d), when the beginnings of a Karman-type vortex street are evident in the wake of the upstream member. However, although the general details of this regime appear to be similar to those found in the wake of a single tube at the same Reynolds number, Figure 2(e), Fox[5] has shown the shedding process to be somewhat disturbed.

Fox[5] measured the Strouhal number of shedding in the gap between similar tubes for axis spacings of up to 10 diameters at a Reynolds number of $Re=2\times10^4$ under the wind tunnel test conditions described in Fox and Toy.[1] The results are presented in Figure 3 and show that the value of the Strouhal number, St, associated with a tube spacing of $L=3D$ and $L=5D$ is approximately 80% and 93%, respectively, of that recorded at an equivalent location in the wake of a single tube examined in the same experiment. (The single-tube value of 0.19 is in agreement with previous data, Schlichting.[6]) Indeed, Figure 3 reveals that the disturbance effects persist for spacings beyond $L=5D$, and it is not until $L=10D$ that the interference caused by the presence of the downstream tube becomes negligible with regard to the Strouhal number.

The spacing-related flow regimes that occur in the wake of the upstream tube have a considerable effect on the flow conditions around the centerline of the downstream tube, as shown in the photographs in Figure 4. When the tubes are in contact, Figure 4(a), the wake is highly disturbed in comparison to that of the single tube, Figure 2(e), and there is no visual evidence of periodic vortex shedding. This result is consistent with streamwise spatial correlation measurements made by Fox and Toy,[1] which revealed that the fluid motion in the wake at the center of the downstream tube is not correlated with the u-component in the X-direction when the tubes are in contact. This lack of correlation results from the presence of a strong secondary flow structure in the near wake of the tube associated with a pair of horseshoe vortices. Zdravkovich[3] discovered that these vortices are generated about the point of contact and

Notation

D	Diameter of tube
L	Distance between axes of tubes
n	Vortex shedding frequency
Re	Reynolds number, DU_0/ν
St	Strouhal number, nD/U_0
U_0	Mean freestream velocity in X-direction
X	Cartesian coordinate in longitudinal direction
Y	Cartesian coordinate in direction perpendicular to the water tunnel floor
Z	Cartesian coordinate in lateral direction
μ	Dynamic viscosity of fluid
ν	Kinematic viscosity of fluid, μ/ρ
ρ	Density of fluid

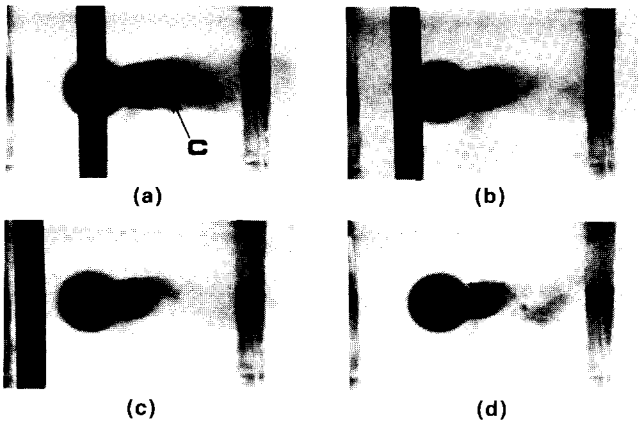

Figure 4 Photographs of the wake at the center of the downstream tube: (a) tubes in contact, $L=1D$; (b) $L=2D$; (c) $L=3D$; (d) $L=5D$. (Freestream flow is from left to right and the Z-direction is perpendicular to the page.)

found that they converge in the near wake, as shown by the intense dye concentration in the region marked by arrow C in Figure 4(a).

Fox[5] went on to show that secondary flow structures persist in the wake of the downstream tube at all axis spacings examined up to 10 diameters but are much weaker in the range $L>3D$. This condition is clearly evident if Figure 4(b), which shows the wake when $L=2D$, is compared with Figure 4(c) and (d) for $L=3D$ and $L=5D$, respectively. Indeed, in the latter case the intense dye concentrations associated with secondary flow are not discernible in the photograph. The wake exhibits the characteristics of periodic vortex shedding, albeit disturbed shedding in comparison with that found in the wake of the single tube, Figure 2(e). This result is again consistent with the spatial correlation measurements of Fox and Toy,[1] who attributed the disturbance effects to the level of turbulence present in the wake of the upstream tube.

Conclusion

The results of this flow visualization study provide details of fluid motion at the center of two tubes arranged perpendicular to each other in the geometry of a cross. The spacing-related flow regimes that occur, both in the gap between each tube and in the near wake of the downstream member, were examined and found to be consistent with measurements made in a wind tunnel study.

Acknowledgment

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