Effect of orientation on the wake of a square cylinder at low Reynolds numbers

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Experimental investigation of flow past a square cylinder at Reynolds numbers of 97 and 187 is reported. Cylinder orientations of 0 to 60° with respect to the mean flow have been considered. Two-component hotwire anemometry has been adopted for velocity measurements. The wake of the cylinder has been visualized using a pulsed laser sheet to understand the flow structure. Measurements have been carried out in the near wake, mid-wake and far wake of the cylinder. The effects of orientation and Reynolds number on Strouhal number, drag coefficient, time-average and rms velocity distributions, decay of velocity fluctuations and power spectra are of interest. There is a dominant peak of vortex shedding in the near wake velocity spectra over the range of Reynolds numbers studied. The Strouhal number and drag coefficient are correlated to the cylinder angle. A change in the cylinder orientation leads to an early appearance of quasi-periodicity and hence three-dimensionality, owing to the asymmetric nature of the wake. The shape of the mean velocity profiles, fluctuations and the rate of decay show a strong dependence on the cylinder orientation in the near wake, though the dependence weakens in the far wake. Among the angles studied, the wake of a cylinder whose orientation is 22.5° with respect to the incoming flow is surprisingly vigorous, and shows strong three-dimensionality. The data of the present work is useful for assessing flow interaction with cylindrical structures of square cross-section.

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Fluid flow past cylindrical objects with non-aerodynamic cross-sections is frequently encountered in engineering applications. Knowledge of the detailed flow field, near as well as away from the object as well as the forces generated are required in the design of structures exposed to a wind load, flow-induced vibrations, acoustic emission and cooling of the electronic equipment. A recent application is the analysis of the wake signature and its correlation to the shape of the object.

Bluff body cross-sections that are frequently employed in applications are circular and rectangular (specifically, square). Circular cross-sections have been extensively studied in the literature. It is well-established that the flow details depend on the Reynolds number, defined on the basis of the average incoming velocity and the characteristic transverse dimension of the body. The wakes behind circular and square cylinders are characterized by a staggered array of vortices, called the Karman vortex street, over a wide range of Reynolds numbers. However, recent studies show that at low Reynolds numbers (Re < 500), the flow is strongly three-dimensional even in nominally two-dimensional geometries. For long slender cylinders with a square cross-section, numerical studies of the wake reveal unusual vortical structures and a complex energy exchange phenomena. The forces acting on a bluff body and the strength of the vortices generated by it are interdependent. It is conceivable that by manipulating the vortex structure in the wake, it is possible to significantly reduce drag. This requires a knowledge of the detailed flow structure in the wake. Considerable research data at high Reynolds numbers (> 2000) have been reported in the literature. However, detailed experimental investigations at low and moderate Reynolds number for flow past slender geometries are limited.

Low Reynolds number wakes have been the subject of investigation in recent years. In an example of heat transfer enhancement, Karniadakis et al. showed that cylinder-induced flow instabilities at a low Reynolds number generate channel wall heat transfer rates comparable to those of turbulent flow, along with significantly less dissipation. Early experiments for low Reynolds number flow past cylinders of rectangular cross-section is the work of Okajima. In this study, the vortex shedding frequency has been reported as a function of Reynolds number, for different width-to-height ratios. Later, Norberg presented experimental results of forces acting on rectangular cylinders of various aspect ratios in the low Reynolds number range. Wake frequencies and the associated Strouhal number were
determined using a hotwire anemometer. Sohankar et al. performed a numerical simulation of flow past a square cylinder at low Reynolds number for different orientations of the cylinder. In the range of incidence angles considered (0<α<45), the onset of vortex shedding occurred within the critical Reynolds number (based on cylinder height) interval of 40 to 55. Results for forces, moments and the Strouhal number were reported by the author. Williamson exhaustively reviewed the physics of three-dimensional vortex dynamics behind a circular cylinder in the Reynolds number range of 100-400. The author discussed the appearance of pronounced three-dimensionality in the flow field even when the geometry is nominally two-dimensional. Recently, Saha et al. performed three-dimensional numerical simulation for flow past a square cylinder at low Reynolds numbers. The authors discussed the spatial evolution of vortices and transition to three-dimensionality behind a square cylinder at zero angle of incidence. Two modes of secondary vortex structures in the transition zone were discussed in terms of their influence on Strouhal number and the time-averaged drag coefficient. The transitional route to three-dimensionality exhibited an intermittent low frequency modulation called vortex dislocation.

The present work reports measurements in the wake of a square cylinder in the low Reynolds number regime, and the effect of cylinder orientation on the flow patterns. The goal of the study is to develop a fundamental understanding of low Reynolds number wakes of a cylinder with a square cross-section (Fig.1), aligned at various angles with the incoming flow. The role of three-dimensionality of the wake in fixing the flow characteristics has been examined. The study is an extension of a previous work of the authors reported at very high Reynolds numbers.

Motivation

The square cylinder is used as a potential vortex generator for passive control of flow in a cooling channel used in gas turbine blades and heat exchangers. The chips in electronic industry also have square/rectangular cross-section. The cooling of chips depends on the fluid flow characteristics past it. The increase in heat flux due to increase in chip density requires better cooling and is a problem of current interest in electronics industries. The orientation of the obstacles with respect to the mean flow will effect the location of separation point between both sides of the cylinder and is therefore expected to influence the effectiveness of square cylinder as a vortex generator. The vorticity dynamics at the wake of the cylinder being different at different cylinder orientations can be beneficial in heat transfer enhancement. The interaction between the flow field of cylinders at different orientation can also enhance the flow controllability. The clear understanding of the flow field is also expected to contribute to better thermal management in electronics industries. This study attempts to understand and present the effect of square cylinder orientation on the detailed flow field.

Apparatus and Instrumentation

Experiments have been carried out in a vertical test cell made of Plexiglas. The overall length of the test cell is 2 m, with a cross-section of 9.5 x 4.5 cm². The active length of the test cell where measurements have been carried out is 0.3 m. The flow in the test section is set up by a blower (WOLF) driven by a single phase motor. The power supply to the blower was through an online UPS (UNILINE) to ensure a practically constant input voltage to the motor. In turn, this had the effect of minimizing the velocity fluctuations in the flow approaching the cylinder. Consequently, the free stream turbulence level in the approach flow was quite small; it was found to be less than the background noise of the anemometer (< 0.05%). Flow parallelism in the approach flow was better than 98% over 95% of the width of the test cell. The cylinder was prismatic in shape, with a

![Fig. 1: Schematic drawing of a square cylinder placed at an angle of θ to the incoming flow.](image-url)
square cross-section of 3 mm edge. The cylinder was made of brass that was machined along its length to preserve its sharp corners. The photograph of the experimental setup of the present study is shown in Fig. 2.

Stable velocities in the range of 0.5-2 m/s were realized in the test cell to cover the low Reynolds number range of 100-400. Measurements of time-averaged velocity and velocity fluctuations were carried out with a DANTEC hotwire anemometer. An X-wire probe was used for measuring two components of velocity. With the square cylinder placed horizontally, the probe axis was parallel to the cylinder, and the X itself was formed in the vertical plane. The two wires of the probe were calibrated against a pitot-static tube connected to a digital manometer (FURNESS CONTROLS, rated for measurements up to 19.99 mm H₂O). The anemometer output voltage was collected in a PC through a data acquisition card with LabVIEW software. The measurement procedure adopted in the present work is similar to that reported earlier⁷.

In the low velocity regime, measurements with the pitot-static tube as well as the hotwire anemometer are prone to errors. These can arise from higher order physical phenomena as well as probe interference effects. The errors can be controlled by using a pitot-static tube of small diameter (2 mm in the present study); in addition the hotwire probe in the present work operated at a lower temperature (of around 150°C) minimizes free convection and radiation errors, without a loss of sensitivity. The accuracy of measurement was affirmed by examining the published Strouhal number-Reynolds number data for a circular cylinder in the range of low Reynolds numbers⁸.

The hotwire probes were calibrated against the pitot-static tube in the vertical test cell itself, in the absence of the square cylinder. Hotwire signals of 20 s length were used to calculate the time-average velocity and the rms velocity fluctuations. The velocity data was reduced from the time series of anemometer voltage signals using the method of Chew and Simpson⁹. A definite positive value of the average velocity in the stream-wise direction was recorded at a dimensionless distance of \( x = 5 \). Measurements ahead of this location were not carried out, since the hotwire probe cannot resolve the sign of the \( x \)-component of velocity, in regions of reversed flow. The power spectra of the velocity fluctuations were determined using the FFT algorithm. The sampling frequency used was 1000 Hz, the signal length being 20. A band pass filter in the range of 0.1 Hz to 1 kHz was additionally used. The vortex shedding frequency was measured at a non-dimensional distance of \( x = 5 \) from the cylinder center-line, at an offset location of \( y = 1.3 \), away from the mid-plane of the flow field. The non-dimensional form of the vortex shedding frequency is the Strouhal number. The drag per unit length (and hence the drag coefficient) was measured using the wake survey method. Here, the time-averaged velocity distribution was utilized at a dimensionless distance of \( x = 15 \) from the cylinder center.

Flow visualization was carried out in the vertical test cell using a light sheet of pulsed Nd:YAG laser. The images were recorded with a CCD camera (OXFORD) synchronized with the firing of the laser. The light sheet and the camera were aligned perpendicular to each other. The flow was seeded with small diameter oil droplets that were produced by a commercial particle generator (LASKIN). Visualization was carried out in the near wake of the cylinder. Images were acquired through a PC at a frame grabber rate of 8 Hz.
The repeatability of the experimental data was ascertained using the following procedure. Measurements were carried out with a cylinder of size 5 mm (instead of 3 mm), while keeping the Reynolds number unchanged. The two sets of data compared well within ± 3%, in terms of the time-averaged velocity and velocity fluctuations in dimensionless form. The agreement in terms of the Strouhal number was much better. These are indicative of a high degree of repeatability in the statistical properties of the flow field.

**Results and Discussion**

The primary interest in the present experiments is to examine the sensitivity of the wake of the cylinder to its orientation with respect to the incoming flow at low Reynolds numbers. The change in the angle of the approach flow affects the wake primarily due to the following two factors: (i) the change in the projected dimension normal to the flow and (ii) the change in the position of the dividing streamline over the cylinder. The dividing streamlines of the approach flow are symmetric at θ=0° and 45° leading to a symmetric velocity profile in the wake. However, at θ=22.5° and 30°, the dividing streamlines evolve asymmetrically, leading to an asymmetric wake behind the cylinder. Hence, the minimum in the u-velocity is not observed at the y=0 location. Instead, it is to be seen at a location y>0, above the mid-plane of the flow field. The effect of the increase in projected dimension can be observed from the magnitude of the u-velocity. At θ=45°, the projected dimension is the largest. Correspondingly, the lowest minimum u-velocity is realized for this angle, downstream of the wake in comparison to all other angles.

To bring into discussion the change in the projected area of the cylinder cross-section, the drag coefficient and the Strouhal number have been defined on the basis of the cylinder dimension (D) blocking the flow, rather than the cylinder size B. Reynolds number continues to be defined on the basis of B, to emphasize the fact that the flow conditions were kept identical in all experiments, irrespective of the cylinder orientation.

Cylinder wakes at low and high Reynolds number can be compared in the following manner. For a circular cylinder, the point of separation is Reynolds number dependent. Hence properties such as the wake size, drag coefficient and Strouhal number exhibit strong dependence on Reynolds number. For a square cylinder, the points of separation are fixed at the upstream corners, and the dependence on Reynolds number is less severe. There is a possibility of flow detaching from the upstream corner, closing in on the cylinder and separating once again from the rear corners. These phenomena are, however, specific to high Reynolds number flows. They are also specific to square cylinders at zero angle of incidence. When the square cylinder is inclined to the mean flow, only one pair of corners contribute to flow separation. Hence, these orientations display only a weak dependence on Reynolds number. This discussion indicates that the time-averaged and bulk properties of the wake of objects with sharp corners would show only a marginal dependence on Reynolds number. However, the size of the turbulent structures and the broadening of the power spectra are dependent on the diffusion and dissipation mechanisms in the wake. These are clearly sensitive to Reynolds number, particularly when Re is towards the lower end of the scale.

Flow separation from the corners of the square cylinder is shown in Fig. 3. The remarkable similarity of these images with the smoke visualization photographs of Dutta et al. at high Reynolds numbers is to be noted. The fixed location of separation points indicates that the results at low Reynolds numbers are likely to be similar to those reported at high Reynolds numbers. The flow visualization results in Fig. 3 indicate that both the stream-wise (X) location at which the separation takes place and the cross-stream (Y) distance between the point of separation at both sides of the cylinder is a function of cylinder orientation. The boundary condition experienced by the flow after separation is also different at both sides of the cylinder.

**Time-averaged velocity and rms fluctuations**

Fig. 4 shows the time-averaged profiles of the x-component of velocity in the direction transverse to the main flow, for several orientations of the cylinder. A Reynolds number of 187 has been considered. With an increase in the downstream distance, a recovery in the center-line velocity takes place. The wake becomes broader due to entrainment of the fluid into the wake. The recovery of the center-line velocity is closely related to the fluid drawn into the wake, and hence the extent of pressure difference between the core of the wake and the external flow. A rapid recovery indicates a substantial pressure difference, that in turn would appear as a higher drag acting on the cylinder. Alternatively, it can be interpreted as the
momentum loss of the fluid that would appear as force acting on the cylinder. Fig. 4 shows that the position of the velocity minimum is along the centerline for symmetric configurations of $\theta=0$ and $45^\circ$. For other angles, the minimum shifts away from the mid-plane ($y=0$) in the near wake ($x < 5$). Farther downstream, the position of the minimum returns closer to the mid-plane location for all cylinder angles.

Fig. 3—Flow visualization in the near wake of the cylinder for different orientations ($Re=275$).

Fig. 4—Time averaged $u$-velocity profile for different cylinder orientations at $Re=187$.

Fig. 5—Profiles of rms velocity at $Re=97$ and 187 for four cylinder orientations.
Fig. 5 shows the non-dimensional $u_{rms}$ profile for $Re=97$ and 187 at three downstream locations and four cylinder orientations. The rms values of velocity fluctuations have been non-dimensionalized with the average incoming velocity. It is seen in Fig. 5 that the $u$-fluctuation decays in the downstream direction. The rate of decay depends largely on the cylinder orientation, being the fastest for the zero angle. The marginally slower decay at other angles is related to the generation of large-scale structures compared to $\theta=0$. The large-scale structures survive break-up and viscous diffusion over a longer distance in the downstream direction. For all angles, the rms profiles show a local minimum at the cylinder centerline in the near wake ($x=5$), along with a peak on each side. This trend is visible at both Reynolds numbers. It is in confirmation with the work of Saha\textsuperscript{10} who has conducted a numerical study of low Reynolds number flow past a square cylinder at zero angle of incidence. In the downstream direction, the individual peaks in velocity fluctuations merge at the center-line where a single maximum is observed. In this respect, the flow field becomes independent of the object shape for locations $x > 15$.

The $u_{rms}$ fluctuation profile broadens in the downstream direction. In this respect, it is similar to the time-averaged velocity profile in Fig. 4. However, the width of the fluctuation profile is marginally greater than that of the time-averaged velocity profile. This is indicative of the significance of diffusion and dissipation phenomena at the scale of the velocity fluctuations in the far field region. Specifically, this result shows that the transport of the time-averaged velocity in the transverse direction is driven by the pressure difference between the wake interior and the free stream; the kinetic energy of the fluctuations are transported by this mechanism, as well as by eddy transport, resulting in a broader wake for the rms quantities. Consequently, the fluctuations decay faster in the stream-wise direction (Fig. 5), when compared to the rate of recovery of the center-line velocity (Fig. 4).

The asymmetric behaviour in the time-averaged $u$-velocity profile that was seen for $\theta=22.5^\circ$ and $30^\circ$ is observed once again in the near-wake velocity fluctuations of Fig. 5. The overall reduction in the magnitude of the fluctuations in the downstream direction is a function of the approach angle. Experiments show that the magnitude of the maximum in $u$-fluctuations is greater than that of the $v$-fluctuations, confirming once again the presence of an additional transport mechanism in the transverse direction for the kinetic energy of the fluctuations. The effect of Reynolds number on the velocity fluctuations is greater in the near field region ($x=5$) in comparison to the intermediate ($x=10$) and the far wakes ($x=15$). The fluctuations relative to the average incoming velocity are also higher at the higher Reynolds number. The maximum value of the fluctuations in the velocity components is a function of the approach angle. It is a minimum at $\theta=0^\circ$, because the size of the vortices produced here are the smallest. The effect of the cylinder orientation on the velocity fluctuation is more pronounced in the near field ($x=5$) than in the intermediate field ($x=10$). The $u_{rms}$ fluctuation at $x =5$ is observed to be a maximum for $\theta=30^\circ$ among all the cylinder orientations. This is attributed to the fact that the dividing streamline of the approach flow that bifurcates at the cylinder is most skewed at $\theta=30^\circ$ in comparison to other orientations.

**Mean vorticity**

The time-averaged vorticity profile is shown in Fig. 6 at three locations ($x =5, 10$ and $15$) downstream of the cylinder, for a Reynolds number of $Re=187$. Vorticity values have been calculated by differentiating time averaged $u$-velocity distribution with respect to the $y$-coordinate. From the plot, it is seen that vorticity has one maximum and one minimum, at each stream-wise location. This is evidence of two oppositely oriented vortices being transported in the wake. The magnitude of the...
vorticity peak largely depends on the orientation angle, and less on Reynolds number. In fact, the appearance of two peaks in vorticity was reported by the authors in their experiments at high Reynolds numbers (Dutta et al.). However, the positions of the vorticity peaks at low Reynolds numbers are found to change with downstream distance for the cylinder orientations considered. This result is in contrast to the comparable experiments at high Reynolds numbers.

The movement of the vortices generated at the corners of the cylinder is controlled by two opposing factors: one is the lower average pressure within the wake. This is opposed by the growing wake size transverse to the main flow, and thus a shift of the vortex center outwards. The second factor is more significant at lower Reynolds numbers, since viscous diffusion aids momentum transfer in the transverse direction, along with transport by the time-dependent transverse velocity field. The cylinder orientation also plays a role, since the vortices emerge from the forward corner of the cylinder for \( \theta = 0 \), but from the rear corners at other angles.

**Drag coefficient and Strouhal number**

Drag coefficient and Strouhal number are quantities of great importance in the design of structures against unsteady fluid forces. Their dependence on the cylinder orientation at Reynolds numbers of 97 and 187 is discussed below.

At low Reynolds numbers, orientation plays a major role in determining the wake size. The flow gets sufficient time to adjust to the geometry of the cylinder. This explains the trend in Fig. 7 that the drag coefficient is sensitive to the angle \( \theta \). Table 1 shows the results for drag coefficient reported by various authors at two Reynolds numbers for zero angle of incidence. The present experimental results are close to the values reported by the earlier investigators.

A comparison of the time-averaged drag coefficient for different cylinder orientations with the numerical work by Sohankar et al. is presented in Fig. 7. Reynolds numbers of 97 as well as 187 have been considered in the plot. It is to be seen that the drag coefficient is sensitive to Reynolds number as well as the incidence angle of the incoming flow with respect to the cylinder. The numerical and the experimental drag coefficients are close to one another; however, experiments show a reduction in the drag coefficient with increasing angle, particularly at \( \text{Re}=187 \). The numerical data shows an opposite trend. The difference can be attributed to the following factors: (i) the experimental results are based on mid-plane measurements, while the numerical simulation is an average over all axial positions of the cylinder; (ii) experiments were conducted with a longer cylinder, when compared to the one adopted for simulation, and (iii) the approach flow in simulation had no superimposed fluctuations, while in experiments these are necessarily non-zero. Factors (i) and (ii) indirectly confirm that the flow is three-dimensional to a point where the average properties of the flow field are influenced by it.

Table 2 shows the Strouhal number obtained by various authors for Reynolds numbers of 100 and 200 respectively for \( 0^\circ \) incidence. Differences in the results with the present experiments are within the experimental uncertainty, and can be attributed to the incoming flow conditions, blockage ratio and free stream turbulence of the approach flow. The difficulties with full three-dimensional numerical simulation of chaotic flow are also quite significant.

<table>
<thead>
<tr>
<th>Angle(( \theta ))</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
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<tbody>
<tr>
<td>( C_D ) (Re=97)</td>
<td>1.60</td>
<td>1.46</td>
<td>1.42</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
</tr>
<tr>
<td>Sohankar et al. (Re=100)</td>
<td>1.51</td>
<td>1.46</td>
<td>1.42</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
</tr>
<tr>
<td>Present (Re=187)</td>
<td>1.51</td>
<td>1.46</td>
<td>1.42</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
</tr>
<tr>
<td>Sohankar et al. (Re =200)</td>
<td>1.51</td>
<td>1.46</td>
<td>1.42</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
<td>1.38</td>
<td>1.45</td>
<td>1.41</td>
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</table>

Fig. 7—Comparison of drag coefficient from experiments with numerical simulation of Sohankar et al.
Fig. 8 shows the variation of Strouhal number with orientation of the cylinder at two Reynolds numbers. The experimental results are compared with the numerical results obtained by Sohankar et al.\textsuperscript{4}. The Strouhal number is seen in the present study to be higher at all incidence angles when compared to θ=0. This is due to a shift in the separation point that causes an increase in the feeding velocity around the lower base corner. The movement of separation points increases the wake size. On the other hand, the separated shear layer rolls up over a shorter distance in comparison to wake size. Numerical simulation shows a continuous increase in Strouhal number with an increase in the approach angle. Experiments also show an increase in Strouhal number with angle, with the exception that a maximum is seen at θ=22.5°. The difference between the experimental and numerical results can once again be attributed to the differences in the reference conditions between them. However, the authors believe that the experimental data at θ=22.5° correctly reveals a maximum in flow acceleration on each side of the cylinder, leading to the greatest increase in Strouhal number.

**Power spectra**

The u-component velocity spectra at different approach angles for Re=97 and 187 are presented respectively in Fig. 9(a-b) and Fig. 10(a-b). The power spectra in Fig. 9 shows a dominant peak indicating clear vortex shedding for all approach angles at Re=97. The power spectra at Re=187 (Fig. 10) also indicates clear dominant frequencies for all approach angles. However, the spectra has a broad-band behaviour for Re=187 at θ=30°, 45° and 60° in comparison to that at Re=97. This indicates that the wake unsteadiness is quasi-periodic at higher approach angles and at higher Reynolds numbers. For lower approach angles, the vortices are alternately shed. The vortices on both sides of the line of symmetry are of equal strength, try to pull each other and hence are responsible for an enhanced signal strength. However, for higher approach angles the interaction between the vortices at the opposite sides of the symmetry are of different strengths, leading to aperiodic vortex shedding and hence broad-band spectrum. Figs 9b and 10b show the velocity spectra at x=10 for Re=97 and 187 respectively. At θ=0° and 22.5°, the power spectra in Fig. 9b continues to show significant periodicity at Re=97. However, the power spectrum is broad-band at θ=30° and 45° for Re=97 at x=10 in comparison to x=5. This indicates the significance of vortex dislocation and diffusion phenomena (Williamson\textsuperscript{5}). Fig. 10b also shows the important role played by vortex dislocation and vortex diffusion phenomena in broadening the power spectra at higher Reynolds number\textsuperscript{5}.

**Flow visualization**

Flow visualization images are shown in Figs 3(a-d) for four different orientation angles. It is seen from the figure that clock-wise and anti-clock-wise vortices are alternately shed from the cylinder. An increase in the distance over which the shear layer curls up is a measure of the reduction in the vortex shedding frequency. The greatest distance is seen for θ=0. The vortex strength decreases as it moves downstream, while the wake size increases. It is observed that the size of the wake increases with angle though not monotonically. The flow structure becomes more vigorous with increasing angle, though the spatial distribution of the flow structure at θ=22.5° shows three-dimensionality and a strong temporal activity. This result is in agreement with the spectral peaks in velocity. The vortex patterns confirm that flow becomes quasi-periodic for cylinder angles greater than zero, at the low Reynolds number range studied.

<table>
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<tr>
<th>Table 2—Comparison of the experimentally measured Strouhal number with other investigations for a square cylinder with zero degree orientation.</th>
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<tbody>
<tr>
<td>( \text{St (Re=100)} )</td>
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<tr>
<td>0.139</td>
</tr>
<tr>
<td>0.140</td>
</tr>
<tr>
<td>0.158</td>
</tr>
<tr>
<td>0.152</td>
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<tr>
<td>0.126</td>
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</table>

Fig. 8—Comparison of Strouhal number from experiments with numerical simulation of Sohankar et al.\textsuperscript{4}
The effect of orientation angle of the cylinder is more significant in the near wake region compared to the far wake region. The size of the re-circulation zone where no tracer particles are able to reach (dark region) located behind the cylinder is highest for $\theta = 0^\circ$. However, the re-circulation bubble is temporal in nature at other inclination angles and the maximum size of the re-circulation zone is smaller than that at $\theta = 0^\circ$. The size of the re-circulation zone is observed to be minimum at $\theta = 22.5^\circ$. The size of the large scale vortices are higher at higher orientation angle. The large size vortices have lower convective velocity and therefore lower Strouhal number, which have been observed from the power spectrum. At $\theta = 22.5^\circ$, the higher near wake activity is responsible in accelerating the vortex and therefore the higher Strouhal number is observed at $\theta = 22.5^\circ$. The large scale vortices do contain small scale vortical...
structures at orientation angle $\theta > 0^\circ$ indicating early transition to three-dimensionality. The higher drag coefficient at $\theta = 22.5^\circ$ can be correlated to larger size of the near wake region due to the effect of transverse flow. The presence of small scale vortices also leads to higher growth of the wake size in the downstream direction due to viscous diffusion. Overall, the flow visualization results explain the bulk behaviour, i.e., $C_D$, $St$ and velocity profiles of the cylinder at different orientations to the mean flow.

Fig. 10 — Power spectra of $u$-component of velocity for $Re=187$ at $X/B = 5$ and 10, $Y/B=1.3$ at five cylinder orientations
Fig. 11—Flow visualization images of the wake as a function of the cylinder angle. Time separation between images is 0.25s (Re=275).
Low versus high Reynolds number

The following is a direct comparison of the wake quantities in the low (< 200) and the high (> 8000) Reynolds number regimes. The high Re data has been taken from Dutta et al.7.

1. The drag coefficient at low Reynolds numbers is in the range 1.15-1.41; at high Reynolds numbers, it is in the range 2.21-2.27.
2. The Strouhal number at low Reynolds numbers is in the range 0.126-0.154; at high Reynolds numbers, it is in the range of 0.141-0.143.
3. The wake sizes in the two Reynolds number regimes are similar.
4. Vorticity decays faster at low Reynolds numbers in the downstream direction, when compared to the high. In fact, at high Reynolds numbers, the vorticity magnitudes barely decrease with distance.
5. At low Re, the evolution of the center-line velocity with distance is faster when compared to high Re.
6. Non-dimensional velocity fluctuations are generally of a lower magnitude at low Reynolds numbers, as compared to high. In both cases, the fluctuations show a strong dependence on the cylinder orientation.
7. The integral quantities such as $C_D$ and $St$ show a continuous variation with angle at low Reynolds numbers. This variation is marginal for high Reynolds numbers, in particular for orientations $\theta > 0$.
8. An examination of the power spectra shows the onset of quasi-periodicity at axial locations of $x > 10$ for all angles at Re=187. For angles beyond $30^\circ$, the onset can be seen at $x=5$ itself. At Re=97, the flow for all cylinder orientations is purely periodic for $x < 5$. In addition, the spectra at Re=97 broaden over the distance $5 < x < 10$ for all angles greater than $30^\circ$. At high Reynolds numbers, the power spectra are uniformly noisy at all angles and positions. Based on the spectral information, it can be predicted that the flow is invariably three-dimensional on the small scale at high Reynolds numbers. However, at low Reynolds numbers, the appearance of three-dimensionality can be correlated to quasi-periodicity, that depends on the cylinder angle and Reynolds number.

Conclusions

An experimental study of flow past a square cylinder at various orientations with respect to the incoming flow has been reported. Two Reynolds numbers (Re=97 and 187) and five cylinder orientations ($\theta=0, 22.5, 30, 45$ and $60^\circ$) have been considered. The mean and fluctuating velocity components, in-plane vorticity component, power spectra, Strouhal number and drag coefficient results are discussed. Experiments show that the change in the orientation of the cylinder leads to early transition to three-dimensionality and appearance of asymmetric wake behaviour. Both Strouhal number and drag coefficient respond strongly to the orientation of the cylinder, and hence preserve information about the shape of the cylinder. The asymmetric nature of the wake profile is responsible for early appearance of quasi-periodicity and is confirmed from the flow visualization images.

Nomenclature

$B =$ edge of the square cylinder (m)
$D =$ projected dimension normal to the flow direction, $= B (\cos \theta + \sin \theta)$ (m)
$C_D =$ drag coefficient, $= \text{Drag per unit length} / \frac{1}{2} \rho U^2 D$
$f =$ vortex shedding frequency (Hz)
$St =$ Strouhal number, $f D / U$
$Re =$ Reynolds number, $\rho UB / \mu$
$x, y =$ dimensional co-ordinates measured from cylinder center (m)
$x, y =$ dimensionless co-ordinates measured from cylinder center.
$u_{rms} =$ x-component velocity fluctuation (m/s)
$v_{rms} =$ y-component velocity fluctuation (m/s)
$U =$ upstream velocity (m/sec)
$u =$ x-component velocity (m/sec)
$v =$ y-component velocity (m/sec)
$\theta =$ cylinder orientation with incoming flow (degrees)
$\rho =$ fluid density (kg/m$^3$)
$\mu =$ dynamic viscosity (kg/m-sec)
$\omega =$ in-plane vorticity component (sec$^{-1}$)

References