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Experimental Study of Near Wake Flow Behind a Rectangular Cylinder

Abdollah Shadaram, Mahdi Azimi Fard and Noorallah Rostamy
Faculty of Mechanical Engineering, Toosi University of Technology,
P.O. Box 19395-1999, Tehran, Iran

Abstract: The turbulence characteristics of the near wake flow behind a rectangular cylinder is investigated in a two-dimensional analysis using a hot-wire anemometer. The time-averaged and fluctuating components of the velocity are measured for a cylinder having various width-to-height ($b\ h^{-1}$) ratios. The measurements are carried out in a low-speed wind tunnel. Data from hot-wire anemometer is collected by a data acquisition system. The results show that the turbulence intensity in the flow wake decreases as the width-to-height ratio of the cylinder increases. In addition, the characteristics of the flow field in a few sections are evaluated. Spectral analysis of the velocity signals is carried out for two different Reynolds numbers. The spectral analysis shows that Strouhal number remains nearly constant in high Reynolds numbers. The results of present experiments are in close agreement with the most widely accepted results in the literature.

Key words: Hot wire, rectangular cylinder, near wake, spectral analysis

INTRODUCTION

In many mechanical engineering applications, separated flows often appear around any object. The flows over steps and fences and flow around high-rise buildings, chimneys and similar structures, are examples of fluid flow with separation around the object. In these cases, the study of wake region behind the model and separation of flow have been considered by many researchers[1,6]. Understanding the wake dynamics predominantly determines the distribution of forces on the object as well as flow-induced vibration and heat transfer rates.

The flows which past the symmetric and asymmetric bodies have been simulated numerically by different researchers and their results have been compared with the experimental results of others[7,8]. Okajima[1] investigated experimentally the flow past a square cylinder at wide range of Reynolds numbers. His study was directed toward the frequency of vortices shed using water channels and wind tunnels. Okajima showed that the Strouhal number and the flow pattern over the rectangular cylinder change with the Reynolds number and width- to- height ratio of a cylinder.

Durao *et al.*[2] investigated closely the wake of a square cylinder in a uniform flow using a laser Doppler velocimetry (LDV) in a water channel at a Reynolds number of 14000. They separated the random and periodic components of the velocity fluctuations in their investigation. Also, they showed that the kinetic energy associated with the random components is approximately 40% of the total kinetic energy. Lyn *et al.*[3] investigated the turbulent flow past a square cylinder at Reynolds number of 21400 with LDV in a water channel. They compared the differences in the length and velocity scales and celerity of the vortices of flows around the square and circular cylinders. Their experimental results showed a relationship between the flow topology and the turbulence distribution. Yao *et al.*[4] and Nakagava *et al.*[5] confirmed that the periodically shed vortices from the cylinder enhance the heat transfer at the downstream channel wall. A simultaneous measurement of the velocity and temperature fluctuation using the hot and cold wires was conducted by Yao *et al.*[4]. They studied the turbulent momentum and heat transfer in a channel flow with a square cylinder. They concluded that in order to clarify the mechanism of heat transfer enhancement, detailed measurement of a flow field is necessary.

Nakagava *et al.*[5] showed that for the channel flow, depending on the width-to-height ratio ($b\ h^{-1}$) of the rectangular cylinder, heat transfer characteristics change significantly. They conducted their experiments in a blockage ratio of 0.2. They also exhibited that for $b\ h^{-1}>2$, the separated flows reattach to the side walls of the cylinder at the leading edge, but for $b\ h^{-1}<1$, those are immediately entrained behind the cylinder and do

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Corresponding Author: Abdollah Shadaram, Faculty of Mechanical Engineering, Toosi University of Technology,
P.O. Box 19395-1999, Tehran, Iran

not reattach to the side walls. For b h^{-1} = 2, the simultaneous reattachment to the upper and lower side surfaces occurs intermittently, which results in the appearance of narrow and wide width of the wake.

The flow past a square cylinder was investigated experimentally by Saha *et al.*[6] using a 2-D hotwire anemometer in a wind tunnel at high Reynolds numbers. In their experiments the time-averaged velocities, as well as the fluctuations, were recorded at both streamwise and transverse directions. They presented the time-averaged profiles of the turbulent shear stresses for two Reynolds numbers of 8700 and 17625. They also investigated the effect of inlet turbulence on the wake flow characteristic.

Grigoriadis *et al.*[7] computed the flow past a square cylinder at a Reynolds number of 22000 using large eddy simulation (LES). They compared the result with the experimental results of other researchers.

Cheng *et al.*[8] presented the computation of flow past a rectangular cylinder using latic-boltzman numerical method at Reynolds numbers of 50-200. They investigated the effect of Reynolds number and shearing rate on drag forces and vortex- shedding.

Turki *et al.*[10] investigated the blockage ratio (β) in their work. They showed that the data would be acceptable for $\beta \leq 0.16$ and would not be reliable for $\beta > 0.25$.

Regarding the previous studies, the present article supplements the results of those studies, by providing further experimental information and close investigation on the wake flow of a rectangular cylinder at various b h^{-1}.

In the present study, the effect of dimensionless parameters such as width-to-height ratio, Reynolds number and Strouhal number on flow characteristics are reported in more acceptable blockage ratios.

In addition, the time-averaged and fluctuating components of velocity at streamwise and transverse directions are presented and compared with other existing results. Spectral analysis of the wake flow and vortex- shedding frequencies are also reported. The frequency of vortex shedding was measured by the spectrum analyzer using the FFT algorithm.

MATERIALS AND METHODS

The present experiments were carried out in an open circuit low-speed wind tunnel made by Plint and was used to simulate uniform air flow. The wind tunnel had a fan with a maximum power of 5.7 kW. The test-section was 305 mm x 305 mm cross-section and 600mm length. Air speed at the test section varied from 3 to 40 m sec^{-1}. The velocity of air was controlled by a throttle valve at the end part of the tunnel. The test section was made of Plexiglas. A schematic diagram of the test section is shown in Fig. 1. For each experiment both air speed and turbulent intensity were measured without the model and used as the reference condition for the flow condition.

The rectangular cylinders were installed symmetrically in the test section. The cylinders were 305mm long and completely spanned the channel. The heights of all cylinders (h) were 15 mm with various width (b). The cylinders were made of plexiglass. The surfaces of the models were smooth enough, so that the roughness effect was negligible.

Air passed through a contraction and a uniform flow passed through the test section with a free stream velocity of U_∞. Reynolds number, Re_h, was defined base on the free stream velocity, U_∞ and the height of the model, h.

Data acquisition was done at different sections normal to centerline direction. Turbulence intensity was 0.02 of the free stream velocity and the distribution of mean velocity was considered to be uniform at the inlet of the test section (Fig. 1).

The x^* stands for the streamwise dimensionless distance from the rear surface of the rectangular cylinder.

Measurements were carried out by a constant temperature hot wire anemometer (CTA) using a 3-D wire probe model 55P91 from Dantec Co. The probe was mounted on a traversing mechanism that facilitated all three orthogonal movements. In order to move the probe in the test section, an open slot with 2 cm wide was made over the wind tunnel's topside. The probe position in the streamwise and cross-stream directions was controllable within 0.5 mm intervals by software.

Before each test, the probe was calibrated for the range of 0.5-30 m sec^{-1} with accordance to the conditions of the test room. Data analysis was made by special program called Streamware. Ambient temperature and pressure were 23±1°C and 668 mmHg, respectively. The signals from the hot wire anemometer were recorded with the digital data recorder at a sampling frequency of 1 kHz. The time-averaged velocity characteristics were obtained using about 10000 samples.

Unlike many of the previous measurements along the mid-plane of the cylinder, our measurements were carried out in both sides of the centerline in order to validate the results.

The previous studies on square cylinders[2,3,9] showed that there was an inversing flow at dimensionless distance of 0.9. According to the present study, the nearest section to the rear side of the model

Table 1: Experimental and numerical parameters and characteristics of wake for a square cylinder

Specification work	Present work	Cheng *et al.*	Saha *et al.*	Nakagawa *et al.*	Lyun *et al.*	Durao *et al.*
Re_h	8600	200	8750	3000	51400	14000
β	0.05	0.04	0.06	0.2	0.07	0.13
Aspect ratio of Cylinder	20	-----	16	35	9.75	6
Strouhal number	0.13	0.15	0.14	0.13	0.13	0.13
Free stream Turbulence level	0.02	-----	0.05	0.06	0.02	0.06
Measurement method	HWA	Numerical	HWA	LDV	LDV	LDV

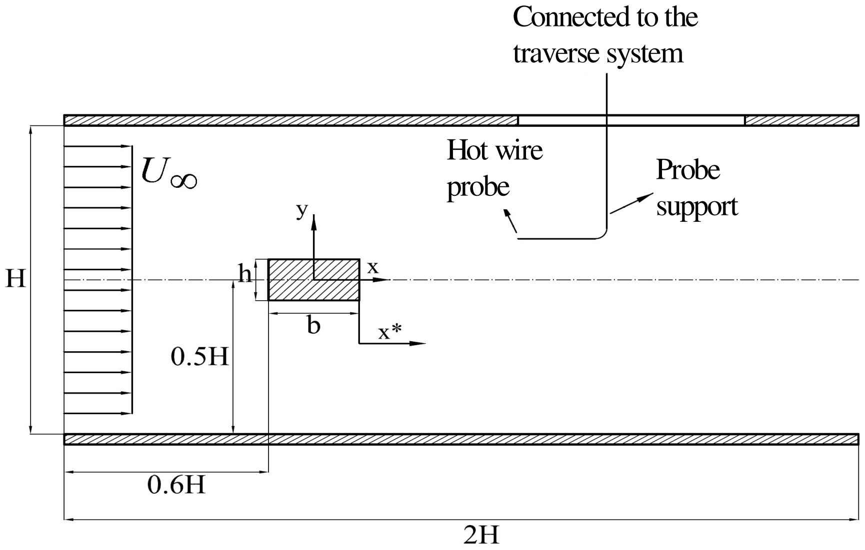


Fig. 1: Schematic diagram of test section

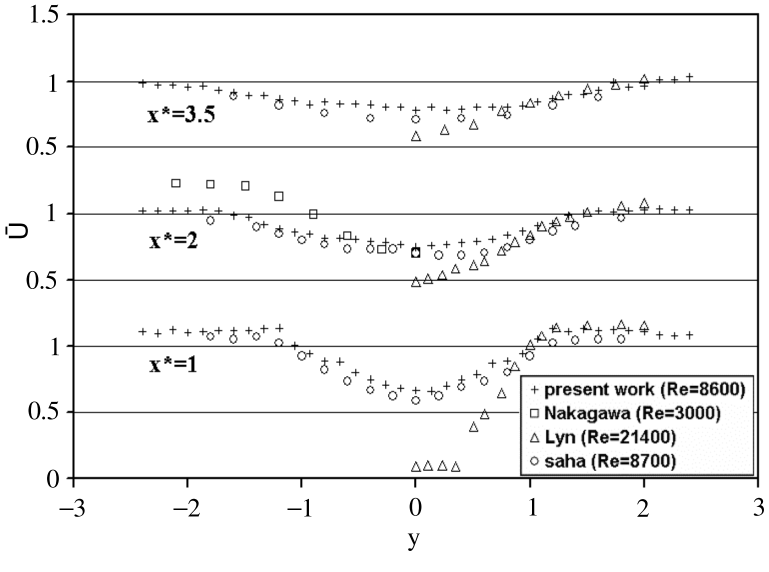


Fig. 2: Profiles of time-averaged streamwise velocity component for b h^{-1} = 1

has been chosen as $x^* = 1.0$. It is due to the effect of inversing flow. The measurement also were carried out in two other sections of $x^* = 2$ and 3, in order to estimate the behavior of the flow characteristic variations. The blockage ratio in present work was 0.05. The number of the measurement points was 111 for three sections normal to centerline and was 56 for centerline direction ($1 \le x^* \le 7.6$).

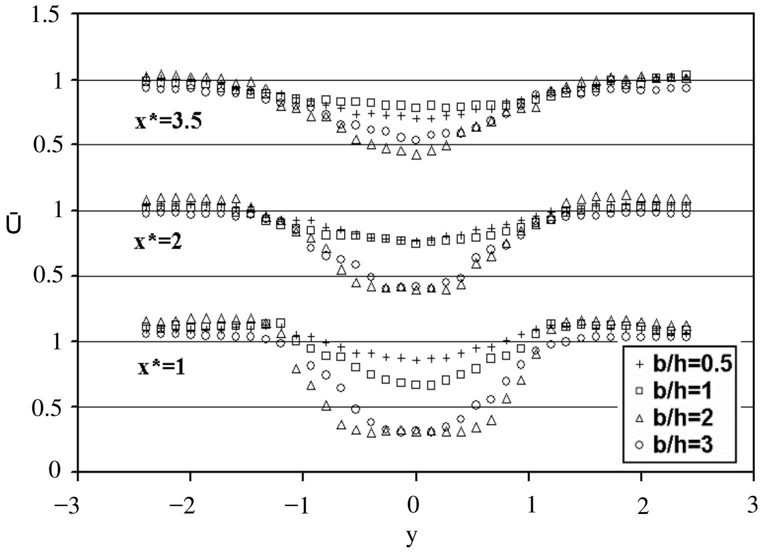


Fig. 3a: Time-averaged velocity component $\bar{U}$ at Re = 8600

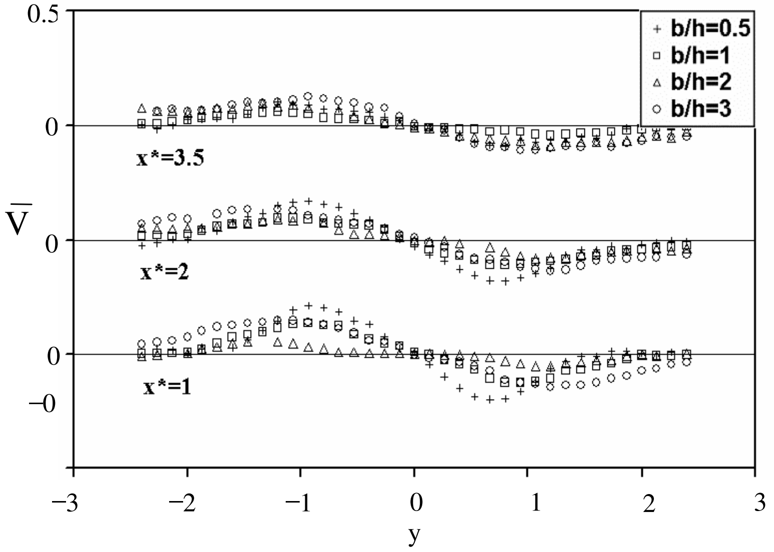


Fig. 3b: Time-averaged velocity component $\bar{V}$ at Re = 8600

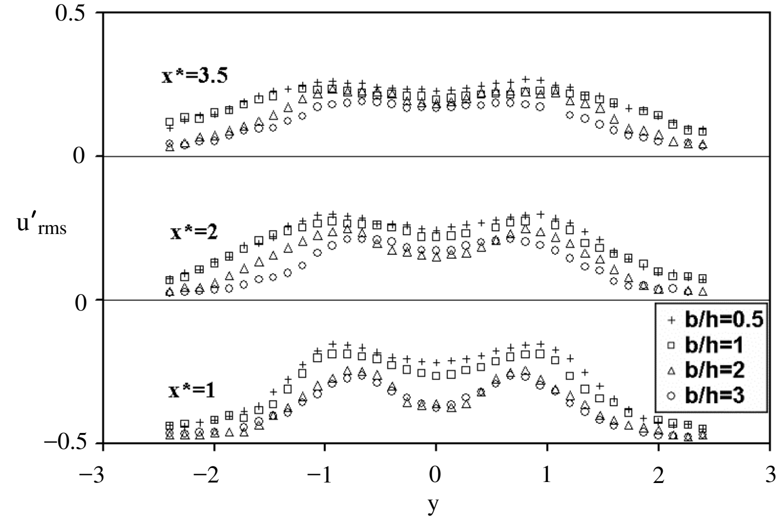
RESULTS AND DISCUSSION

The flow characteristics are determined at both streamwise (x) and normal (y) directions. All distances are non-dimensionalized using the height of the model. U and V are streamwise and normal velocity components respectively. Furthermore, u′ and v′ are the streamwise and normal velocity fluctuating components as well.

The time-averaged velocities and the fluctuating components of the velocity are processed using the related software. The free stream velocity is selected as 17.94 m sec^{-1} and 8.83 m sec^{-1} in order to provide Reynolds numbers of 17400 and 8600, respectively.

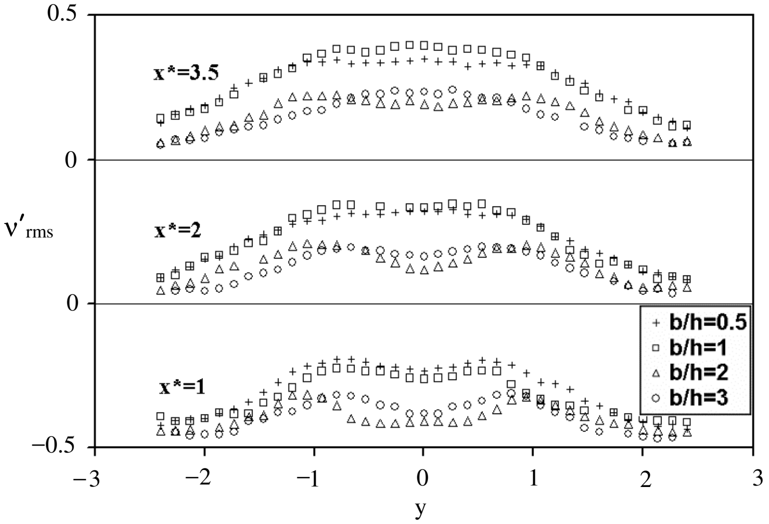
Table 1 summarizes the experimental conditions and the characteristic of wake for a square cylinder. The discrepancy between the present result and the previous results may be explained by the difference in blockage ratios and the upstream conditions of the flow.

Figure 2 shows the profiles of time-averaged streamwise velocity, ($\bar{U}$) for b h^{-1} = 1 at three different sections. These profiles show velocity defects near the



(a)

Fig. 4a: Streamwise fluctuating component of velocity at Re = 8600



(b)

Fig. 4b: Normal fluctuating component of velocity at Re = 8600

centerline along the streamwise direction. The distributions of $\bar{U}$ have been compared with the results obtained by Nakagava *et al.*[9], Saha *et al.*[6] and Lyn *et al*[3].

Figure 3 (a, b) show the time-averaged streamwise ($\bar{U}$) and normal velocity (v) components against y, respectively at different locations and different values of b $\tilde{h}^1$, at Reynolds number of 8600. According to Fig. 3a, there is a velocity defect for all b$\tilde{h}^1$, near the centerline of the test channel. This defect is recovered at locations x = 2 and 3.5.

The constant values of streamwise velocity for large values of b $\tilde{h}^1$ at x = 1 around the centerline represent the inversing flow behind the model whereas there is no inversing flow for b $\tilde{h}^1$ = 0.5 and 1. This behavior is also confirmed by the references[3,9].

Figure 3b shows the normal time-averaged velocity component at Re = 8600. The positive and negative values of the normal velocities indicate that the flow is entrained in the near wake.

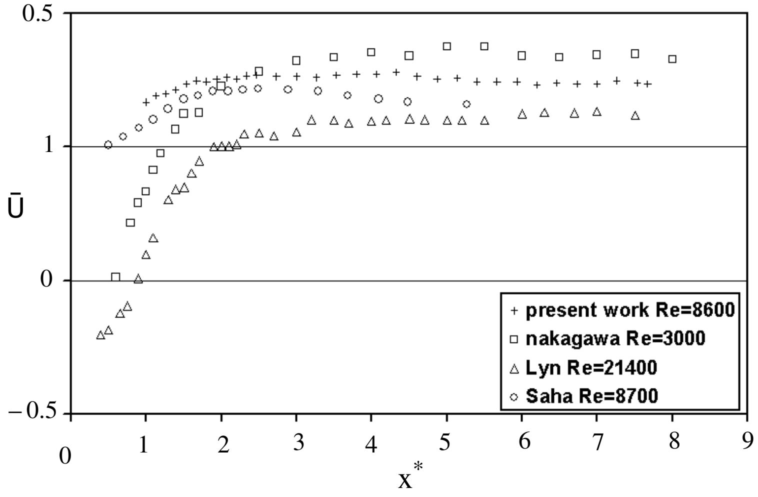


Fig. 5: Centerline distributions of streamwise velocity characteristics for b h^{-1} = 1

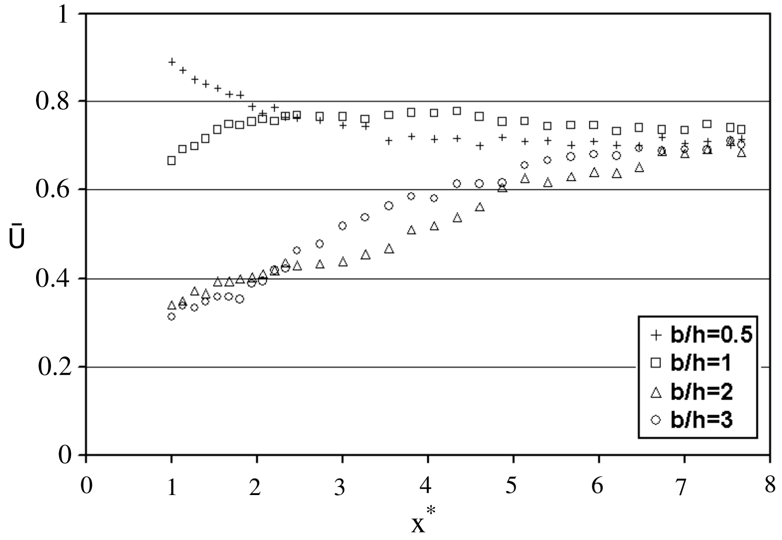
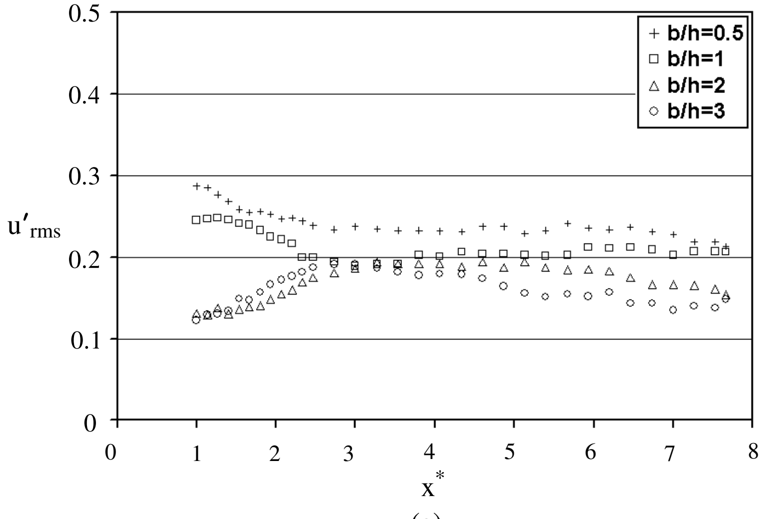


Fig. 6: Centerline distributions of streamwise velocity characteristics for a rectangular cylinder at Re = 8600 for different b h^{-1}

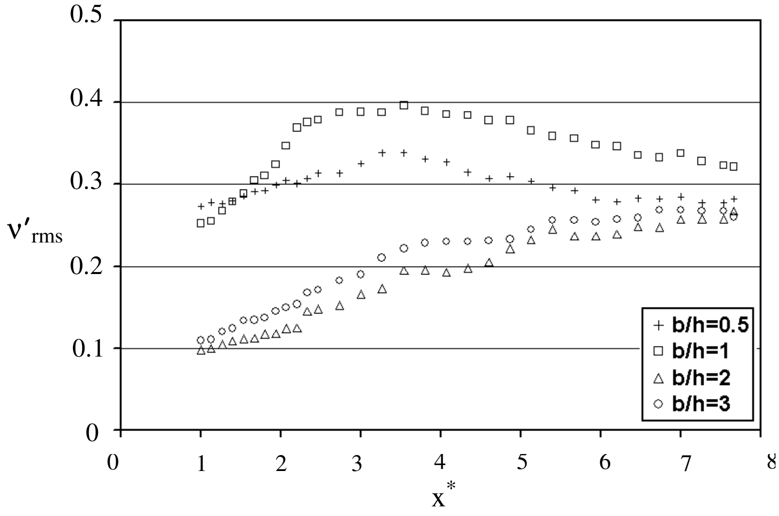
Figure 4 (a,b) show the u'_{rms} and v'_{rms} at different sections of downstream of the model at different b h^{-1}. It can be seen that the maximum values of u'_{rms} occur near the center line of the model. This is due to the interaction between shear layers separated at the leading edge of the model and the wake formed behind the model. These maximum values are declined as the distance from the model increases. Durao[2] pointed out that the wake of a square cylinder has an anisotropic nature. In addition, a high value of turbulent intensity is explained as a result of vortex shedding.

According to Fig. 4b, at large x^* the maximum values of v'_{rms} occur just on the centerline of the model. This is due to the alternative contact of shear layers separated from upper and lower surfaces of the model. Figure 4b shows the transverse velocity fluctuations (v')at three different locations downstream of the cylinder. It can be seen that the transverse fluctuating components of velocity at b h^{-1} = 0.5 and 1 are considerably larger than those at b h^{-1} = 2 and 3. This would be attributed to the strong shed vortices which persist downstream in cases of b h^{-1} = 0.5 and 1.



(a)

Fig. 7a: Centerline distributions of streamwise fluctuating component of velocity at Re = 8600



(b)

Fig. 7b: Centerline distributions of normal fluctuating component of velocity at Re = 8600

Significant values of u'_{rms} and v'_{rms} are revealed at locations near the model ($x^* = 1$ and 2). Meanwhile, at location far enough from the model, both streamwise and transverse fluctuating components of velocity get a uniform shape because the shear layers approach to the centerline of the tunnel.

The time-averaged turbulent quantities differ in profile depending on $b\,h^{-1}$. The turbulent intensities for $b\,h^{-1} = 0.5$ and 1, are larger over the cross section of the channel than those of the other cases. This implies the shedding of stronger vortices from the cylinder. When $b\,h^{-1}$ is large, the shear flows separated at the leading edge of the cylinder reattach to the side wall of the cylinder and separate again at the trailing edge. As a result, according to Fig. 4a and b, the positions of maximum u'_{rms} and v'_{rms} move inward when $b\,h^{-1}>1$. It means that at $b\,h^{-1} = 0.5$ and 1 the maximum values of velocity fluctuating components are closer to the centerline than those of $b\,h^{-1} = 2$ and 3.

Figure 5 shows the distributions of $\bar{U}$ on the centerline of the channel for a square cylinder ($b\,h^{-1} = 1$). Present results are compared with the results obtained by Lyn *et al.*[3], Saha *et al.*[6] and Nakagava[9]. In this figure, the abscissa is a non-dimensional

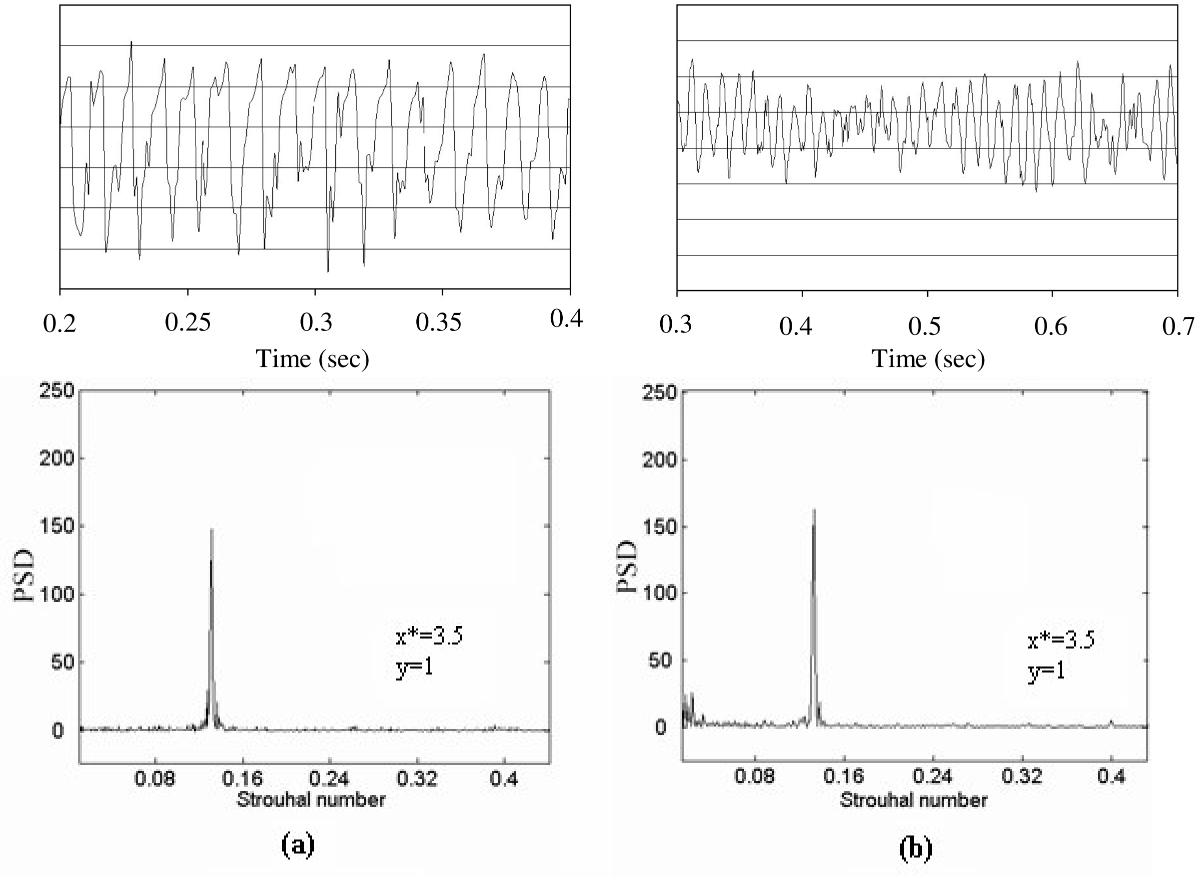


Fig. 8: Comparison of measured velocity fluctuations and the power spectra for a square cylinder: a) Re = 8600; b) Re = 17480

streamwise distance from the rear surface of the cylinder. The present results are in agreement with those of Saha *et al.*[6] due to their close Reynolds numbers. The discrepancy in these two works can be explained by the difference in turbulent intensity of the main flow.

Figure 6 shows the distribution of $\bar{U}$ on the centerline for different values of b h^{-1} at a Reynolds number of 8600. According to this figure, for low aspect ratios, the recovery of the velocity is faster than those of high aspect ratios. This may be explained by the difference in length of the near wake region.

Figure 7a and b show the centerline distributions of streamwise and normal turbulence intensity for different aspect ratios at Re = 8600. As it is seen from the Fig. 7a, the streamwise turbulent intensities reach their maxima near the rear stagnation point of the recirculation region. Since the length of near wake region is rather large for b h^{-1} = 2 and 3, the entrainment of separated flow behind the cylinder as well as the shed vortices is rather weak.

In the cases of b h^{-1} = 0.5 and 1, the recovery of the velocity defect is relatively slow, though the length of near wake region is small. This would be attributed to the strong shed vortices which persist downstream at farther downstream region compared to the other cases[5].

SPECTRAL ANALYSIS OF WAKE FLOW

According to the high frequency responses of the Hot-wire anemometer, it might be useful to present some features of turbulence spectra in this work. Furthermore, since hot-wire experiments reveal local point wise information; it is usually cumbersome to map the flow field in all respects. Instead, the power spectra of x and y components of velocity determined at selected locations in the wake can shed light on the wake dynamics. With these objectives, the U spectra are recorded both along the centerline (y = 0) and an offset position (y = 1.0) at two Reynolds numbers of 8600 and 17480.

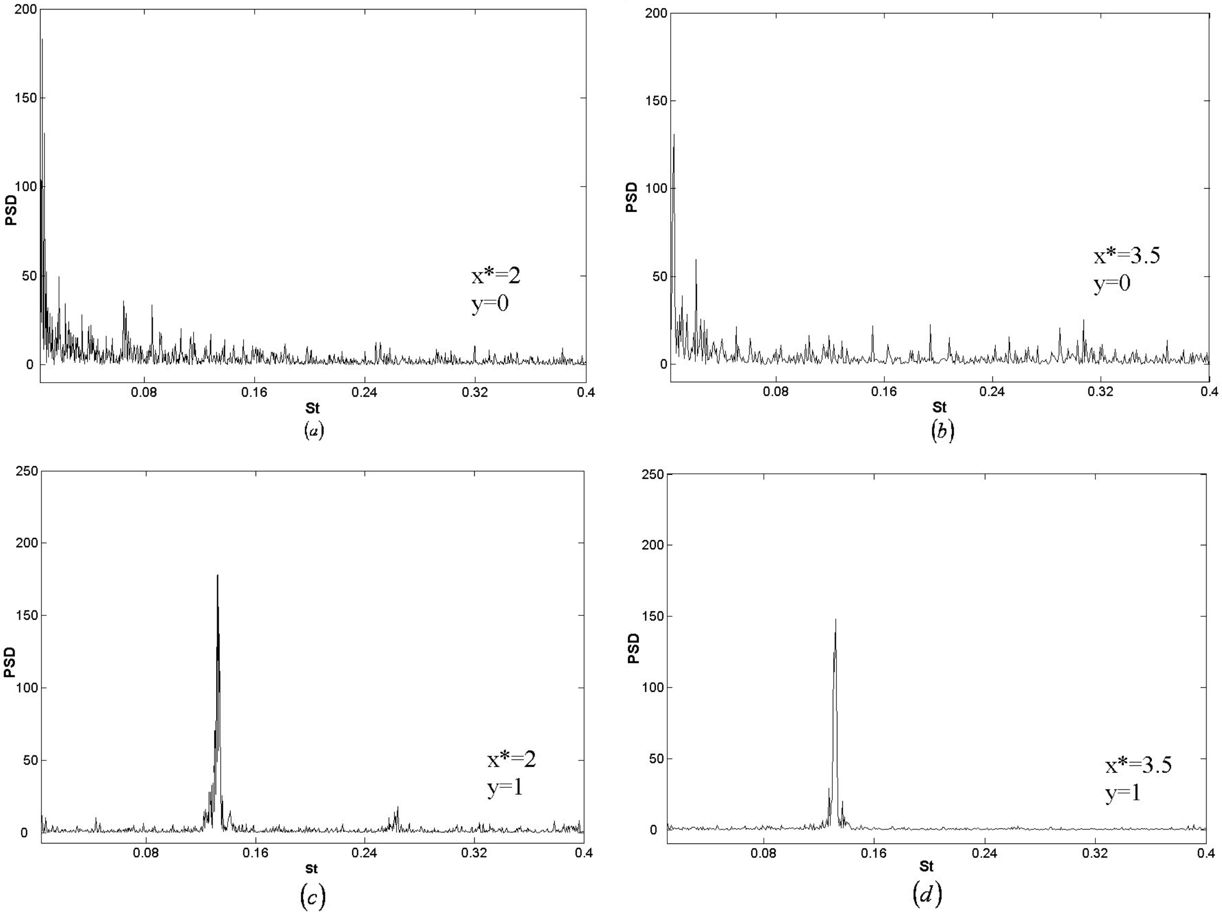


Fig. 9: U spectra at various streamwise locations foe a square cylinder at Re = 8600: a, b) centerline (y = 0) c ,d) offset position of y = 1.0

Figure 8a shows a part of recorded signals in the wake flow of a square cylinder (b h^{-1} = 1) along an offset position of y=1 for Reynolds number of 8600 at x^* = 3.5. The near-wake spectra at y = 1.0 are calculated using Fast Fourier Transform (FFT) and plotted in Strouhal number.

According to Fig. 8, the recorded velocity fluctuations have an oscillating behavior. In addition, Fig. 8 clearly brings out a dominant peak at the shedding frequency (Strouhal number of 0.13).

Figure 8b shows the recorded signals and the power spectra for a square cylinder at Reynolds number of 17480 along at offset position (y = 1.0) at x^* = 3.5.

Comparing the Fig. 8a and b, it is considered that the Strouhal number of the square cylinder is not changed as the Reynolds number increases.

The same Strouhal number can be seen for present work and the references[2,3,5] according to table 1.

Figure 9 shows the U spectra at locations x^* = 2 and 3.5 for two y plane in the wake of a square cylinder at Reynolds number of 8600. Along the centerline, the spectra do not reveal a dominant peak, but there is a dominant peak at the shedding frequency, particularly when the probe is away from the centerline. At higher x locations, the U spectra tend to become broader with a peak developing close to the origin. Furthermore, the peak in the U-spectra seen at the offset location diminishes in strength for greater x-locations[6]. According to Fig. 9c, the second harmonic is seen to be excited at dimensionless frequency of 0.27, signifying the influence of vortices shed from the cylinder on the probe.

CONCLUSION

Near wake of a rectangular cylinder has been studied experimentally at Reynolds numbers of 8600 and 17400 using Hot-wire anemometer. The cylinder width is varied so that the width-to-height ratios ($b\ h^{-1}$) are 0.5, 1, 2 and 3.

Analysis of the flow in the near wake of rectangular cylinders having different width-to-height ratios, shows that the velocity defects are low in the cases of $b\ h^{-1} = 0.5$ and 1. The normal components of velocity are strongly entrained in the near wake region at low $b\ h^{-1}$. There are two maximum values for fluctuating components of the velocity near the centerline because of the interaction between the shear layers of upper and lower surfaces of cylinders and the wake region.

The variations of velocity fluctuating components are symmetric to the centerline. The turbulent intensities for $b\ h^{-1} = 0.5$ and 1 are larger over the cross section of the channel than those of the other cases because of the shedding of stronger vortices from the cylinder.

Since the shear flows separated at the leading edge of the cylinder reattach to the side wall of the cylinder and separated again in the trailing edge, the near wake region is longer in the cases of large $b\ h^{-1}$ than those of low $b\ h^{-1}$.

The spectral analysis of the flow shows that the shedding frequency (Strouhal number) is not changed as the Reynolds number increases. At greater x^*, the power spectra of velocity fluctuations decreases.

LIST OF SYMBOLS

x	Streamwise coordinate measured from the center of the cylinder
y	Transverse coordinate measured from the center of the cylinder
x^*	Streamwise dimensionless distance measured from the rear surface of the cylinder
H	Height of the test section, m
h	Height of the cylinder, m
B	Width of the cylinder
F	Frequency of vortex shedding, Hz
U_∞	Mean flow velocity
U, V	Streamwise and transverse components of velocity
$\bar{U}, \overline{V}$	Streamwise and transverse time-averaged components of velocity
	Streamwise and transverse fluctuating components of velocity
u'_{rms}, v'_{rms}	Streamwise and transverse root mean squared velocities
Re_h	Reynolds number based on height of the cylinder
St	Strouhal number, $fh\ U^{-\infty}$
β	Blockage ratio

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