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ON SEPARATED SHEAR LAYER OF BLUNT CIRCULAR CYLINDER*

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ABSTRACT: Separated shear layer of blunt circular cylinder has been experimentally investigated for the Reynolds numbers (based on the diameter) ranging from 2.8×10^3 to 1.0×10^5, with emphasis on evolution of separated shear layer, its structure and distribution of Reynolds shear stress and turbulence kinetic energy. The results demonstrate that laminar separated shear layer experiences $2 \sim 3$ times vortex merging before it reattaches, and turbulence separated shear layer takes $5 \sim 6$ times vortex merging. In addition, relationship between dimensionless initial frequencies of K-H instability and Reynolds numbers is identified, and reasons for the decay of turbulence kinetic energy and Reynolds shear stress in reattachment region are discussed.

KEY WORDS: blunt circular cylinder, separated flow, shear layer, K-H instability

1 INTRODUCTION

Separated-and-Reattaching flow is a typical shear flow, which arises in many situations of practical interest other than mixing layers, wakes and jets, such as leading-edge flow separation on a thin airfoil or the flow entering a ramjet dump combustor. Despite the simplification associated with the immobility of the point or line of separation, such flows retain a number of fluid-dynamic complexity and have been widely investigated. However, previous works focused on separation flow over a 2D leading-edge blunt plate[1~4], a 2D backward-facing step[5,6], a T-shape structure[7], or a 2D airfoil[8,9], there are only several reports[10~12] on separation flow of blunt circular cylinder. Ota[10,11] and Kiya[12] once investigated the separation flow of blunt circular cylinder, concentrating on mean flow field feature, such as, reattachment length of separated shear layer (X_r), pressure distribution, turbulence fluctuation velocity and mean velocity profile, but involved little dynamic evolution process of separated shear layer.

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In this paper, characteristics of separated shear layer, such as, reattachment length, K-H instability frequency, and turbulence kinetic energy and Reynolds shear stress distribution is determined for Reynolds numbers varying from 2.8×10^3 to 1.0×10^5. Furthermore, evolution of separated shear layer is investigated, and reasons for decrement of turbulence kinetic energy and Reynolds shear stress in reattachment region are discussed.

2 EXPERIMENTAL SETUP

Experiments are conducted in a low-turbulence wind tunnel with flow velocity varying from 0.05 m/s to 20 m/s. The rms turbulence intensity of the free stream is less than 0.08%. The test section is 0.3 m wide, 0.8 m high, and 3.2 m long.

The configuration of flow is shown in Fig.1. The blunt circular cylinder (80 mm diameter and 350 mm long) is made of plexiglass and the leading edge of the cylinder is sharply cut at an angle of 90 deg in order that flow always separates there over the whole circumference. The x axis is in the longitudinal direction, while the y axis is perpendicular to the axis of the cylinder in such a manner that $y = 0$ is located on the cylinder surface.

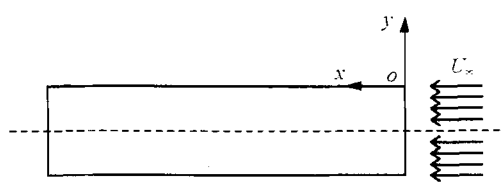


Fig.1 Schematic of flow field and cross-sectional view of blunt circular cylinder

Flow visualization is performed by means of smoke technique and tuffs. The former is for the case of low velocity, and the latter is for high velocity. Reattachment point is a transitory equilibrium point, where the time for smoke (tuffs) to move upstream is equal to that downstream. And distance between separation point and reattachment point is termed as reattachment length.

A TSI-1050 hot-wire anemometer is employed for measuring the fluctuation velocities. The sampling signals are transferred by an A/D convertor to a computer and then processed to obtain the Auto-Power (A-P) spectra, turbulence kinetic energy and Reynolds shear stress.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Separated Shear Layer and Reynolds Numbers

Figure 2 illustrates the variation of turbulence kinetic energy and Reynolds shear stress against Reynolds numbers, and the measurement position is near separation line. For Reynolds number ranging from 2.8×10^3 to 2.4×10^4, turbulence kinetic energy and Reynolds shear stress are low, and separated shear layer remains laminar; on the other hand, for Reynolds number ranging from 3.0×10^4 to 1.0×10^5, the separated shear layer lies in turbulence regime. As a consequence, the separated shear layer is termed as laminar separated shear layer and turbulence separated shear layer respectively, and typical photographs of flow visualization are shown in Fig.3 and Fig.4 separately.

According to flow visualization, the evolution of separated shear layer is slower in low Reynolds numbers than that in high Reynolds numbers, which can be demonstrated by variation of distance between the position of the first vortex rolling up and the separation point (l_r) against Reynolds numbers. As indicated in Fig.5, l_r decreases rapidly with Reynolds numbers increasing, which means the evolution of separated shear layer speeds up and the critical point for separated shear layer becoming instable moves upwards. Furthermore, the higher the Reynolds number is, the smaller the first vortex size is. For laminar separated shear layer, the first vortex is 2D spanwise vortex, and will become three-dimensionlized when it moves downstream, due to the perturbation of recirculation region and the interaction between vortices. With increment of Reynolds number, the position for 2D spanwise vortex becoming 3D vortex gradually moves upwards; for turbulence separated shear layer, the first vortex is 3D. In addition, higher Reynolds number causes a larger increase in entrainment of separation bubble. The increased entrainment corresponds to higher turbulence kinetic energy and Reynolds shear stress (Fig.2), which means transversal momentum exchange and mixing increase.

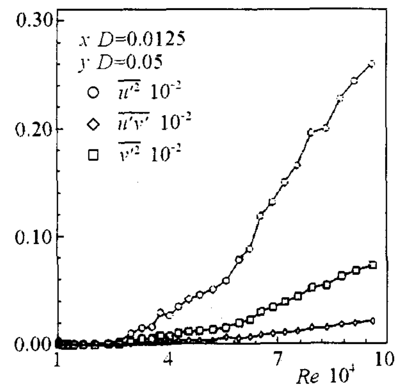


Fig.2 Variation of turbulence kinetic energy and Reynolds shear stress against Reynolds number

Fig.3 Photograph of flow visualization of laminar separated shear layer, $Re = 2.8 \times 10^3$

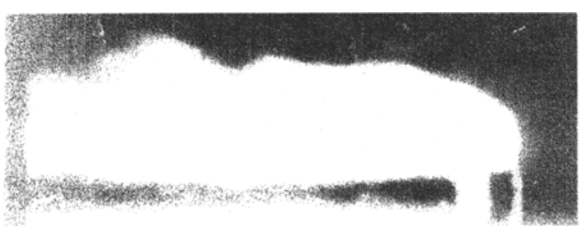


Fig.4 Photograph of flow visualization of turbulence separated shear layer, $Re = 6.4 \times 10^4$

Relationship between dimensionless initial frequencies of K-H instability and Reynolds numbers is illustrated in Fig.6, which can be written as follows,

$$S_t = -1.90727 + 11.6778 \times Re - 9.73174 \times Re^2 + 3.73847 \times Re^3 - 0.617469 \times Re^4 + 0.0376313 \times Re^5$$

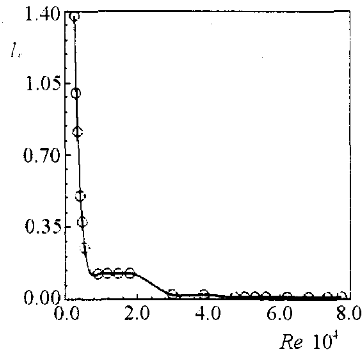


Fig.5 Variation of Distance between separation point and position of the first vortex rolling up against Reynolds number

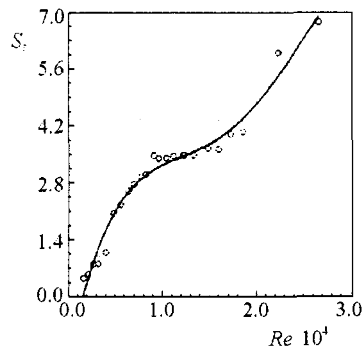


Fig.6 Variation of K-H instability frequency against Reynolds number

where Re lies in the range of 2.0×10^3 to 3.0×10^4. For laminar separated case, the frequency peak in A-P spectrum is narrow and steep (Fig.7(a)); for turbulence separated case, the frequency peak in A-P spectrum becomes broad and broaden with Reynolds numbers increase (Fig.7(b)).

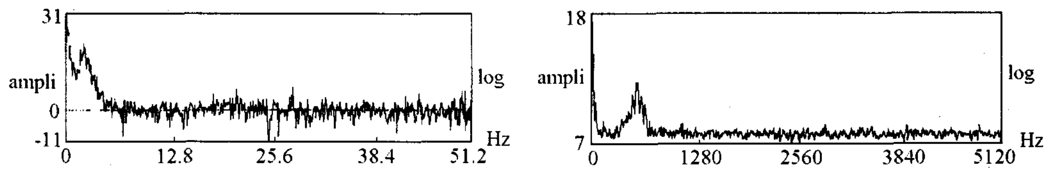


Fig.7 Typical A-P spectra at different Reynolds number

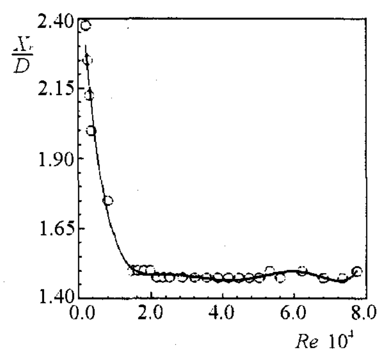


Fig.8 Variation of reattachment length against Reynolds number

Variation of reattachment length of separated shear layer (X_r) against Reynolds numbers is illustrated in Fig.8. For the laminar separated shear layer, X_r decreases rapidly with Reynolds number increase; for turbulence separated shear layer, X_r is independent of Reynolds number, and X_r/D is about $1.4 \sim 1.5$.

Fluids resource of recirculation zone is an area of much interest. When McGuinness[13] studied the large-eddy structure in a separated-and-reattaching shear layer behind an orifice at the entrance of a pipe, he concluded that in the reattachment region some of the large eddies were swept upstream, while others proceeded downstream, and the fluids in the recirculation zone come from eddies swept upstream. Measurements of Chandrasuda et al.[14] and Kim et al.[15] showed that the intermittency is less than unity near the wall just downstream of reattachment, this result supported the hypothesis that the eddies moved alternately up-and downstream. However, Bradshaw & Wong[5] claimed that the eddies were torn roughly in two in the neighborhood of the reattachment point, a part of the eddy went upstream and formed the reverse flow. In our experiments, both modes exist. Besides, there exists the third mode—eddies are swept from the top of separation bubble. Generally, Bradshaw & Wong's mode dominates.

3.2 Laminar Separated Shear Layer

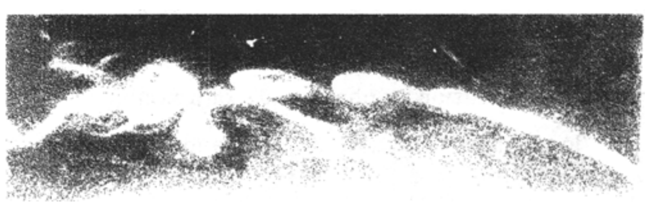
Flow visualization The smoke emitted at the position of $x = 5\,\text{mm}$ moves upstream along the surface of the cylinder, and then turns to the downstream at the separation point. The trajectory of the smoke shows the evolution of the separated shear layer. Figure 3 is a typical photograph of flow visualization taken at Reynolds number $Re = 2.8 \times 10^3$. The laminar separated shear layer could be divided into three regions according to its flow pattern.

The region from the leading edge of the cylinder to the position of the first vortex forming is termed as Regime I, where the K-H instability wave evolves. Near the separation point, the K-H instability wave is very weak and the smoke trajectory is smooth. With the evolution of the separated shear layer, the amplitude of the K-H instability wave gradually grows and the intensity of the vorticity, which is distributed along the surface of the instability K-H waves, also successively increases. The vorticity cumulated and finally results in the spanwise vortices forming.

Regime II, from the position where the first vortex forming to the reattachment point, is the region for the vortices evolving and interacting each other. As the vortices move downstream, they are always displaced to different lateral locations according to the individual phase differences between the vortices and the subharmonic. Owing to the lateral velocity gradient the vortices would acquire different speed, and sometimes a pair of them could merge into a larger one. In the present experiment, vortices merging has mainly two modes, mode I is the case for two vortices merging (Fig.9(a)), and mode II is the case for three vortices merging (Fig.9(b)). As a whole, mode I accounts for about 80% of all cases.

Regime III ranges from the reattachment point further downstream, in which the separated shear layer gradually turns into the boundary layer.

(a) Photograph of flow visualization of two vortices merging



(b) Photograph of flow visualization of three vortices merging

Fig.9

In Regime I, the smoke is concentrated and the spanwise vortices are clear; in Regime II, owing to the three-dimensional disturbances introduced by the fluctuations in the recirculating flow and the vortices' interaction, the smoke is a bit scattered; in Regime III, the smoke is disperse because of the interaction between the large eddy structures and the surface of the cylinder.

According to the flow visualization, it could be concluded that the spanwise vortices in the laminar separated shear layer are caused by the evolution of the K-H instability waves, and the laminar separated shear layer grows by pairing mechanism until it approaches the surface of the cylinder in the reattachment region. From the separation point to the reattachment position the vortices merging will take place 2 $\sim$ 3 times.

Spectra development In Regime I, the strength of the K-H instability wave is quite weak at the initial region of the separated shear layer, thus the K-H instability wave is difficult to detect, there is no frequency peak on the A-P spectrum of the streamwise fluctuation velocity (Fig.10(a)). With the evolution of the K-H instability wave, there appears the peak of the K-H instability frequency on the A-P spectrum and its amplitude increases, but the value of the K-H instability frequency remains constant (Figs.10(b) $\sim$(d)).

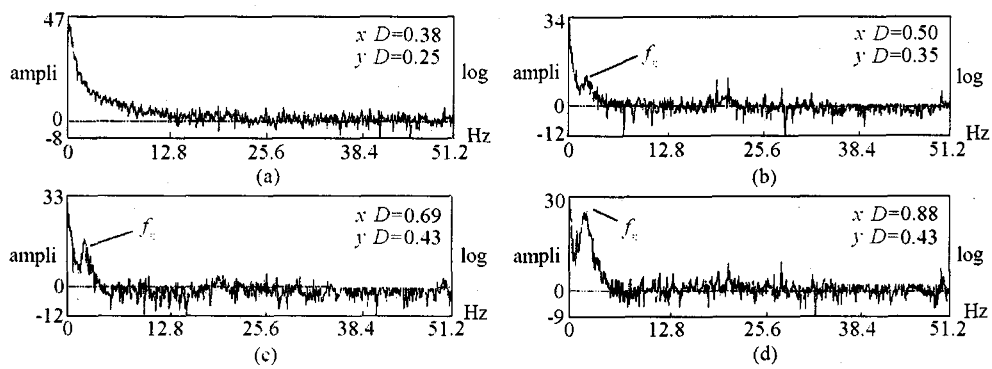


Fig.10 A-P spectra development of laminar separated shear layer in Regime I, $Re = 2.8 \times 10^3$

In Regime II, there is the subharmonic phenomenon, which corresponds to the vortices merging. Figure 11(a) shows the A-P spectrum measured at the position of ($x/D = 1.0625$, $y/D = 0.425$), which is the first vortex shedding position. At the position of ($x/D = 1.1875$, $y/D = 0.425$), the first subharmonic appears, which implies the onset of the vortices merging process (Fig.11(b)). With the measurement position going downstream, the amplitude of the first subharmonic grows (Fig.11(c)) and finally predominates at the position of ($x/D = 1.4375$, $y/D = 0.425$) (Fig.11(d)), which means the first vortices merging process completed. After the first vortices merging process completing, the second vortices merging process takes place further downstream, which is verified by the second subharmonic occurred on the A-P spectrum (Fig.11(e)). The successive subharmonics phenomena in spectrum space correspond to the periodic bifurcation in phase space of a nonlinear dynamical system.

In Regime III, the flow is in the chaotic state, the band of the peak of the K-H instability frequency broadens (Fig.11(f)).

The A-P spectra development demonstrates that the separated shear layer experiences vortice merging processes 2 $\sim$ 3 times.

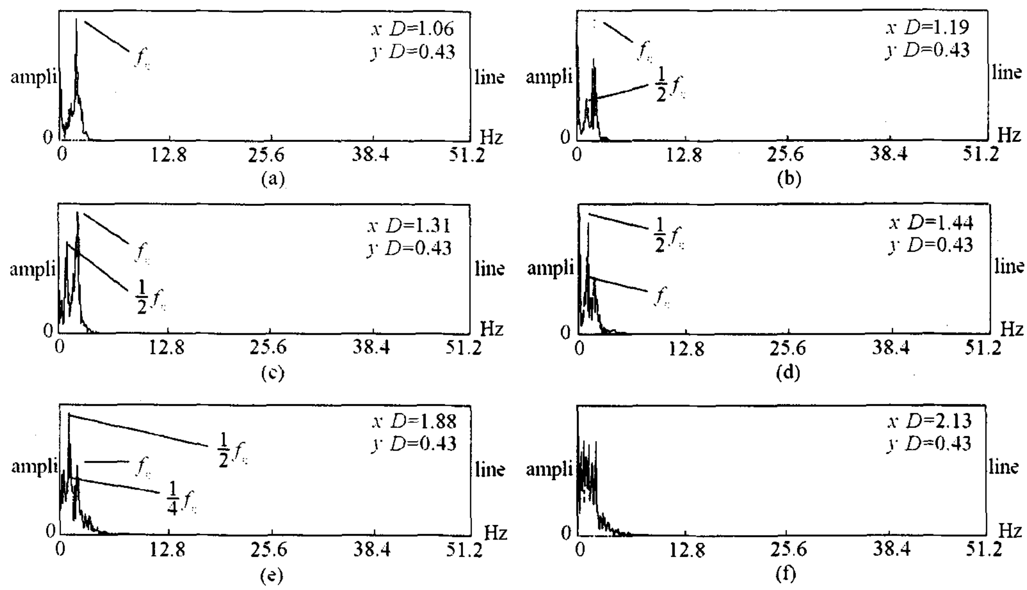


Fig.11 A-P spectra development of laminar separated shear layer
(a)-(e) in Regime II, (f) in Regime III, $Re = 2.8 \times 10^3$

3.3 Turbulence Separated Shear Layer

Flow Visualization For turbulence separated shear layer ($Re > 3.0 \times 10^4$), high turbulence kinetic energy and Reynolds shear stress cause a large entrainment inside the separation bubble (Fig.4).

Spectra Development Table 1 gives A-P spectra development of turbulence separated shear layer at Reynolds numbers $Re = 3.2 \times 10^4$ and $Re = 6.4 \times 10^4$. There also exists subharmonic phenomena in the evolution of turbulence separated shear layer, which indicates large coherence structures merging processes.

Table 1 Spectra development of turbulence separated shear layer

Measurement position	$Re = 3.2 \times 10^4$								
(x/D)	0.0125	0.75	0.2	0.6	0.875	1.438	1.563	2.5	4.375
(y/D)	0.0688	0.2	0.25	0.35	0.4	0.4	0.4	0.4	0.4
f_n(Hz)	1080	540	270	135	65	30	30	30	30
Measurement position	$Re = 6.4 \times 10^4$								
(x/D)	0.038	0.088	0.163	0.375	0.769	1.563	1.875	2.5	4.375
(y/D)	0.044	0.125	0.175	0.32	0.381	0.5	0.5	0.5	0.6
f_n(Hz)	1280	640	330	170	90	42	42	42	42

As indicated in Table 1, from the leading-edge to the reattachment region, the value of center peak frequency of turbulence separated shear layer descends successively by half and half till the shedding frequency of separated shear layer. It will experience $5 \sim 6$ times large coherence structure merging processes.

Turbulence Kinetic Energy and Reynolds Shear Stress As shown in Fig.12, the distribution of turbulence kinetic energy has the same trend as that of Reynolds shear stress, however, the value of Reynolds shear stress is less than that of turbulence kinetic energy, and the value of longitudinal turbulence kinetic energy is less than that of streamwise. The position for the largest turbulence kinetic energy locates near that for the largest Reynolds shear stress, which corresponds to the centerline of separated shear layer (Fig.13). From the leading edge, the values of the largest turbulence kinetic energy and Reynolds shear stress ascend streamwise, and attain the maximum in the reattachment region. However, from the reattachment region further downstream, they descend (Fig.14).

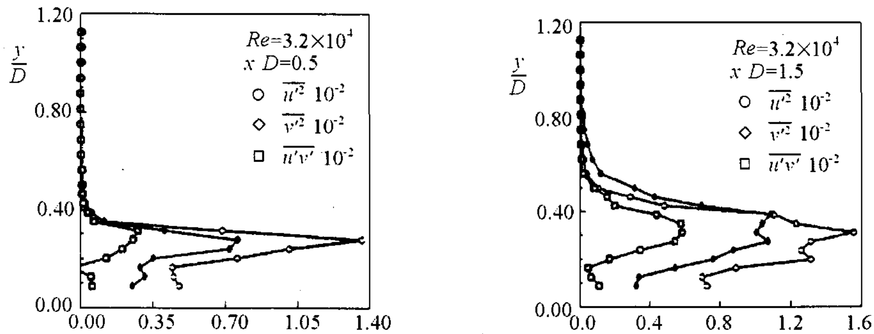


Fig.12 Distribution of turbulence kinetic energy and Reynolds shear stress of turbulence separated shear layer

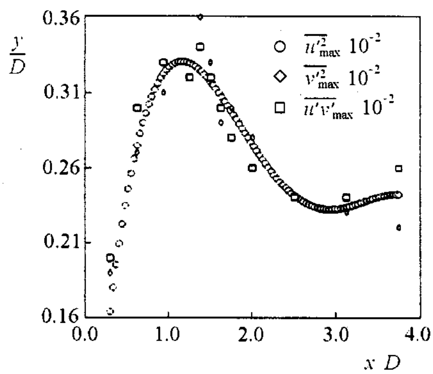


Fig.13 Position of the largest turbulence kinetic energy and Reynolds shear stress occurring, $Re = 3.2 \times 10^4$

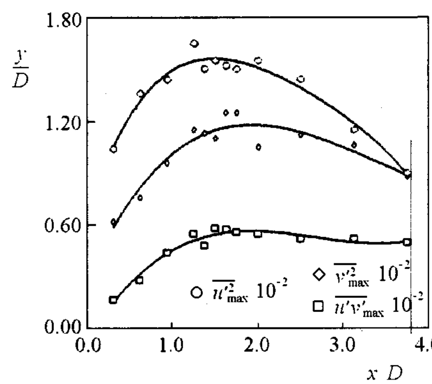


Fig.14 Variation of values of the largest turbulence kinetic energy and Reynolds shear stress along streamwise, $Re = 3.2 \times 10^4$

It is hard to understand the decrease of the turbulence kinetic energy and Reynolds shear stress from the reattachment zone downstream. Bradshaw & Wong[5] concluded that the imposition of the normal velocity constraint by the wall ($v = 0$) and the strong streamwise pressure gradients cause the large eddies to be torn in two in the reattachment region. The rapid reduction in length scale should be responsible for the decreases in the turbulence level. However, other research workers disagreed this argument, and measurements far downstream of the reattachment point indicated that the free-shear-layer structure persists in the outer part of the boundary layer. McGuiness[13] attributed the decay of turbulence kinetic energy and Reynolds shear stress to the fact that some of the large eddies were swept upstream with the recirculating flow, and others proceeded downstream. In fact, either Bradshaw & Wong Mode or McGuiness Mode has an identical feature, i.e., the total vorticity decreases from the reattachment zone downstream, which should be responsible for the decay of the turbulence kinetic energy and Reynolds shear stress.

4 CONCLUDING REMARKS

Separated shear layer of blunt circular cylinder lies in laminar regime for Reynolds number ranging from 2.8×10^3 to 2.4×10^4, and turbulent one for Reynolds number ranging from 3.0×10^4 to 1.0×10^5. Reattachment length of laminar separated shear layer decreases with increasing Reynolds numbers, and that of turbulence separated shear layer is independent of Reynolds number, $X_r/D = 1.4 \sim 1.5$.

The relationship between dimensionless initial frequency of K-H instability and Reynolds number can be written as follows,

$$S_t = -1.90727 + 11.6778 \times Re - 9.73174 \times Re^2 + 3.73847 \times Re^3 - 0.617469 \times Re^4 + 0.0376313 \times Re^5$$

where Re lies in the range of 2.0×10^3 to 3.0×10^4.

Evolution of separated shear layer is slower in low Reynolds number case than that in high Reynolds number one. Furthermore, the higher Reynolds number is, the smaller the first vortex size is. For laminar separated shear layer, the first vortex is 2D spanwise vortex, and will become three-dimensionlized while moves downstream, due to the perturbation of recirculation region and interaction between vortices, moreover, the position for 2D spanwise vortex becoming 3D vortex gradually moves upwards with increasing Reynolds number; for turbulence separated shear layer, the first vortex is 3D.

Fluids in recirculation zone are mainly from three modes:

- The vortices will be torn in two while it interacted with the surface of the cylinder, a part of one large-eddy structure goes upstream, forms reverse flow.
- Some of the large eddies are swept upstream with the recirculating flow.
- Some eddies are swept from the top of separation bubble.

where the dominant mode is the first one.

The vortices in the separated shear layer of the blunt circular cylinder are caused by the evolution of the K-H instability waves. The separated shear layer grows with pairing mechanism until it approaches the surface of the blunt circular cylinder. For laminar separated shear layer, it will experience $2 \sim 3$ times vortices merging processes from the leading edge to the reattachment point; for turbulence separated shear layer, it will take $5 \sim 6$ times vortices merging processes.

The position for the largest turbulence kinetic energy locates near that for the largest Reynolds shear stress, which corresponds to the centerline of separated shear layer. From the leading edge, the values of the largest turbulence kinetic energy and Reynolds shear stress ascend streamwise, and attain the maximum in the reattachment region. However, the total vorticity decreases from the reattachment zone downstream resulting in the decay of the turbulence kinetic energy and Reynolds shear stress.

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