

Research Article

Role of Shape Factor in Wake Width Development at Moderate Reynolds Number

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Abstract:

This paper addresses the wake width variability downstream of bluff bodies with variable shape factors. The numerical investigation is conducted at the laminar vortex shedding regime with moderate Reynolds numbers (Re) ranging from 80 to 160. Shape factor ($S.F.$) is decided by the extent of the bluffness imparted to the rear part of the body, 0.5 being the bluffest, while 2.0 is the streamlined. The results point out that Re had a consistent impact on wake width for all body shapes, while the same couldn't be stated for the shape factor. The shape factor had a non-intrusive effect on wake behaviour, and all shape factor configurations produced wakes of an identical structure at a particular Reynolds number. Quantitative comparisons also indicate that wake width stays on the same scale as projected body length. It seems that the Reynolds number plays a more significant role than shape in establishing wake structure for the laminar regime. The findings of this paper provide relevant information for passive flow control and bluff body design with small geometric variations in moderate Reynolds number regimes.

Keywords: laminar vortex shedding, wake width, shape factor, Reynolds number, time-average fluctuating velocity, Reynolds stresses

1. Introduction

Many Wake dynamics behind bluff bodies have been studied extensively, in part due to their relevance to engineering and environmental applications, such as flow-induced vibration mitigation, aerodynamic drag minimisation, pollutant transport/dispersal, and heat and mass transfer enhancement. The foundational research that established the periodic vortex street forms behind a circular cylinder was published by Kármán (1911), and subsequent experiments/numerical studies have detailed the transition of the wake as the Reynolds number increased. The very first detailed work by Roshko [1] on the vortex shedding and drag calculation behind bluff bodies provides a critical insight into this topic. Moreover, the contributions of Gerrard [2], Bloor [3] and Williamson [4] on detailed classification of the flow and the modes of shedding are considered as the backbone of the modern investigation. The flow around the circular cylindrical body was classified based on its behaviour with respect to. Re . For $Re < 47$, the wake remains steady and symmetric; when $47 < Re < 200$ wake becomes unsteady and periodic, and beyond $Re \approx 200$, the wake finally transitions to turbulence[1]–[4].

An important property for bluff body wake studies is wake width, which gauges the lateral spread of the velocity deficit region downstream of a bluff body. The lateral spread of the wake width is an important factor in wake-induced drag and the periodic wake-induced vortex shedding. At low Re values (typically below 46–50), the bluff body wake

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remains laminar symmetric, (two steady recirculation bubbles present. As Re increases, the bluff bodies wake transitions through symmetry breaking- periodic vortex shedding and laminar wake transitioning into a turbulent wake.

Despite being thoroughly investigated, there is no universally accepted criterion to identify the boundary of the wake width. Various researchers have proposed different theories [5]–[7] to recognise the wake width. The most widely acknowledged theory is the maximum Reynolds Stress (RS) along the wake axis by Bloor et al. [8]. The wake axis is an imaginary centreline or axis that exists at the centre of the wake. The shortest distance between the maximum RS is supposed to indicate the W_d , although the indistinctness in the results of the RS method makes it unsuitable for asymmetric flow.

Much of the older literature was focused on the circular cylinder [9]–[13], but some recent research is investigating various bluff body shapes, such as squares, rectangles, and ellipses [14]–[22]. These studies show that even small changes to the shape and geometry of the blunt body can lead to significant changes in the wake, from modifying the frequency of vortex shedding to having noticeable impacts on the drag coefficient and recirculation length. Effects induced by shape and outline geometry are typically quantified using non-dimensional parameters like the shape factor that correlates to the aspect ratio (height, width) or bluntness of the body. Among the most cited studies that consider wake structure and shape effects appears to be that of Mittal et al. [23] who conducted two-dimensional numerical simulations for a range of bluff body shapes and supplied a comprehensive source of data on vortex shedding characteristics, lift/drag oscillations and wake lengths. They showed that increasing the aspect ratio of elliptical bodies leads to a reduced wake width and delayed onset of vortex shedding.

Another dimension of interest is how the wake width varies spatially downstream. Norberg et al. [24] demonstrated that for canonical shapes like circular cylinders, the wake width grows linearly with streamwise distance until reaching a maximum, after which it decays due to entrainment. However, such trends can shift dramatically for non-circular bodies, particularly in the presence of flow separation modifications. Regarding Reynolds number effects, studies like those by Thompson et al. [24] provided evidence that increasing Re leads to earlier flow separation, stronger shear layer instabilities, and shorter recirculation zones — all of which influence the wake width. Yet, systematic investigations of this behaviour across a wide range of non-standard shapes remain sparse. Thus, knowing how the bluff body wake width changes with shape and Re in the laminar regime (Re 80–160) would aid both a fundamental understanding of fluid mechanics and identify the best practices for design formulations and strategies. Here, we extend the previous work [26], [27] by investigating wake width variability over a laminar vortex shedding regime. The bluff bodies with shape factors (SF) varying from 0.5 to 2.0 in intervals of 0.25 are used to perform two-dimensional laminar flow simulations. The shape factor is defined by the ratio of the streamlined length to the radius of the circular part of the body. This work provides further advances in understanding wake modulation through geometrical design at moderate Reynolds numbers. The results we present here fill an important gap in the literature by systematically mapping how wakes vary with Reynolds number and shape factor in laminar flow.

Further, the paper is divided into a section describing the problem statement and the validation in the methodology section. The methodology section is followed by the results and discussions, while the concluding remarks are given in the last part.

2. Methodology

The primary objective of the work is to analyse how the wake width evolves with both shape and Reynolds number in the laminar regime, specifically for Reynolds numbers (80-160) at the laminar vortex shedding regime. All simulations were carried out using the ANSYS Fluent solver, which offers robust tools for solving pressure-based transient flow problems under incompressible conditions.

2.1 Problem setup

The bluff body was centrally placed within a two-dimensional rectangular computational domain, which was carefully sized to minimise boundary effects and allow adequate wake development. The domain measured $30D$ in height and $60D$ in length, where D represents the characteristic length (diameter or equivalent dimension) of the bluff body. To optimise computational efficiency without sacrificing accuracy, the domain was divided into two distinct

regions: 1 and 2. Both of them share the same face that has 100 divisions (the same goes for N), while O is divided into 80 divisions. Each face in section 1 has 100 divisions, whereas M (0.5D) has equally spaced 40 divisions. Further, the mesh size is matched with the side K, which has 200 divisions. The region surrounding the bluff body and its near-wake zone was refined with a high-density mesh to accurately resolve boundary layer separation and wake recirculation features. Further downstream (section 2), a coarser mesh was employed to reduce computational time while still capturing the global structure of the wake. The computational domain design is illustrated schematically in Figure 1.

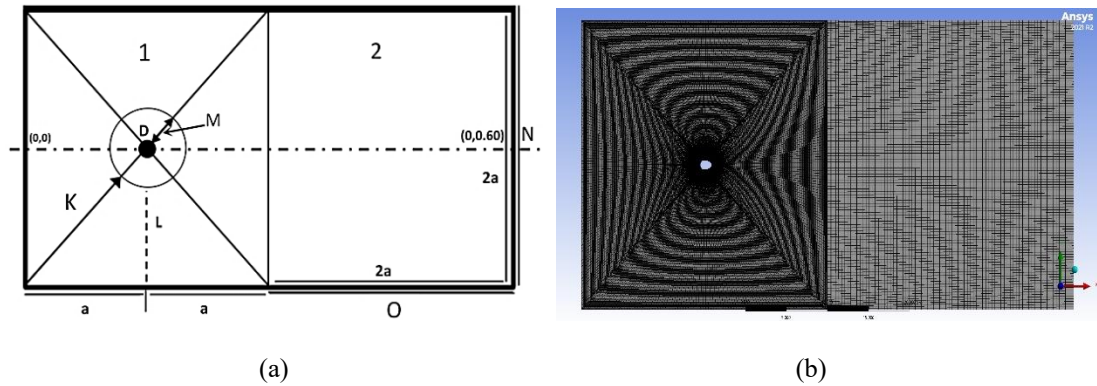


Fig. 1. (a) Domain size where ‘a represents 15D. (b) Structured mesh fluid domain

A series of bluff body geometries was constructed based on a shape factor (S) definition, with S values ranging from 0.5 to 2.0 in uniform increments of 0.25. This approach facilitated a smooth transition from elongated, slender bodies to bluffer, circular-like configurations. Each body in the series maintained the same projected frontal area to ensure a fair basis for comparison across shapes. These bodies were positioned identically within the computational domain, and identical meshing and solver strategies were used for each case to isolate the effects of shape and Reynolds number.

Unlike the previous study, which used air with artificially adjusted properties to achieve low Reynolds numbers, the present simulations employed water as the working fluid to reflect more realistic physical conditions. The fluid properties were set as follows: a density (ρ) of 998.2 kgm^{-3} and a dynamic viscosity (μ) of $0.001003 \text{ kgm}^{-2}\text{s}^{-1}$. The inlet velocity was maintained at a specific velocity defined by the Reynolds number for all cases, and the Reynolds number for each simulation was controlled by selecting the appropriate body size to achieve the target Re values.

Boundary conditions were assigned to facilitate smooth inflow and outflow while ensuring symmetry and realistic no-slip behaviour at the wall. The left boundary of the domain was defined as a velocity inlet with a uniform velocity varied with Re accordingly, while the right boundary was set as a pressure outlet with zero gradients for velocity and pressure to allow for unimpeded flow exit. The same boundary condition has been employed as given in the literature [26], [27], where the top and bottom of the domain are provided with slip conditions while the body has a no-slip condition (shown in Figure 3). For greater accuracy, residuals are set to 10^{-5} , and the time step size is set to 0.02. The initialisation process is done by the implementation of the Hybrid Initialisation Scheme.

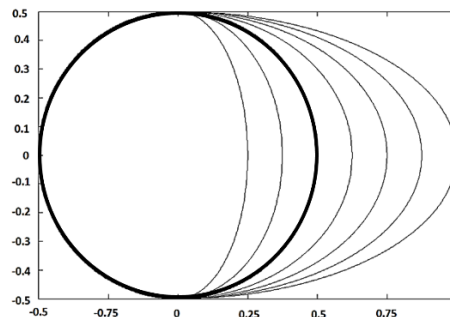


Fig. 2. Variation in shape factor where the bold line circle depicts the base

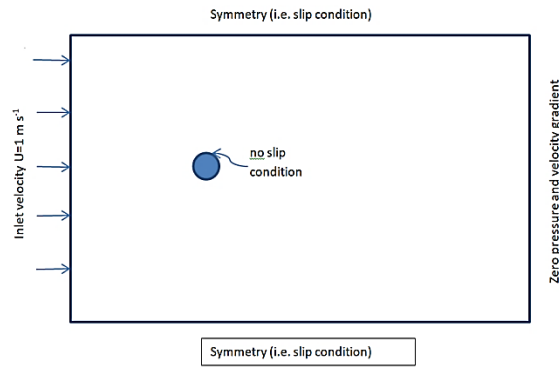


Fig. 3. A schematic diagram of the boundary conditions applied to the fluid domain

2.2 Validation

The mean drag and maximum lift coefficient are calculated till the appropriate division in the L is achieved (Figure 4). Further, the results are matched with the results of the Park [28] and Dobriyal et al. [27] and are given in Table 3.1.

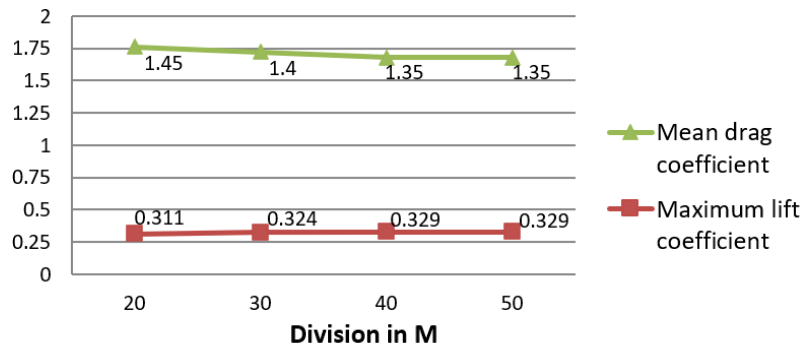


Fig. 4. Grid independence results for the circular cylindrical body (S.F. 1.0)

Table 1: Comparison of drag coefficient of the cylindrical body with Park and Choi [28] and Dobriyal et al. [27] at Re 40 and 60.

Re No.	Park et al.	Dobriyal et al.	Present
40	1.51	1.58	1.560
60	1.39	1.40	1.358
80	1.35	1.37	1.342
100	1.33	1.35	1.325

3. Results and Discussions

The lateral spread of the velocity deficit region at the downstream of the body, which is known as the wake width in the literature. Although wake width is not defined as the region enclosed inside a distinct boundary, several researchers have tried to measure it utilising the time average value of the fluctuation in the streamwise velocity. Norberg [29] explored the flow around a round cylinder. The researcher searched for the spot with the smallest wake width, as here is where vortices develop and begin diffusing convection downstream. He advises defining wake width as the space between maxima of time-averaged stream-wise velocity fluctuations. The stream-wise fluctuating velocity (u') is defined as

$$u' = u - \bar{u} \quad (1)$$

The wake width is marked between the peaks of time-averaged streamwise velocity fluctuations. Figures 5 to 8 (a–e) represent the contours of the time-average of the fluctuation of velocity for each S.F. (0.5 to 2.0) at the given

Reynolds numbers. All the results are calculated for the 6 vortex shedding cycles after the amplitude of the coefficient of fluctuation of lift (C_L) is attained. The contours are shown for the shape factors 0.5, 1.0, 1.50 and 2.0 only, while for the quantitative analysis, the data are represented for each shape factor. Additionally, all the contours are scaled down in a ratio of 1:100.

Wake width is non-dimensionalised with the projected length of the bluff body (D) and given in each contour ($W^*=W_d/D$), and the graph for the quantification is given in the last part of each figure (part (f) of Figures 5–8). There was a consistent and meaningful trend across all simulations, in that as the Reynolds Number increased from 80 to 160, the wake width decreased in a defined and systematic manner. This trend in wake width and Reynolds Number was obtained for each shape factor presented in the study, regardless of the geometry of the body being either streamlined (lower shape factor) or more bluff (higher shape factor). This suggested that increased inertia at high Reynolds Numbers influenced the momentum exchange more in the nebula region, and the rate of narrowing of the wake was increased, hence the lateral extent of the velocity deficit was reduced.

Surprisingly, while shape factor is a well-established variable influencing wake development, with respect to Reynolds Number, shape factor effects seemed to be of minimal influence in this Reynolds Number range. While some variation in wake width was observed with changing shape factor, the wake narrowing trend with an increase in Reynolds Number was largely unaffected by shape factor (Figure 9). This suggested that at least with respect to the laminar transitional regime investigated, Reynolds Numbers may have a definitive impact on wake structure, and shape geometry alone is of lesser importance. These results may provide valuable insights into wake control strategies which apply design objectives without changing Reynolds Numbers.

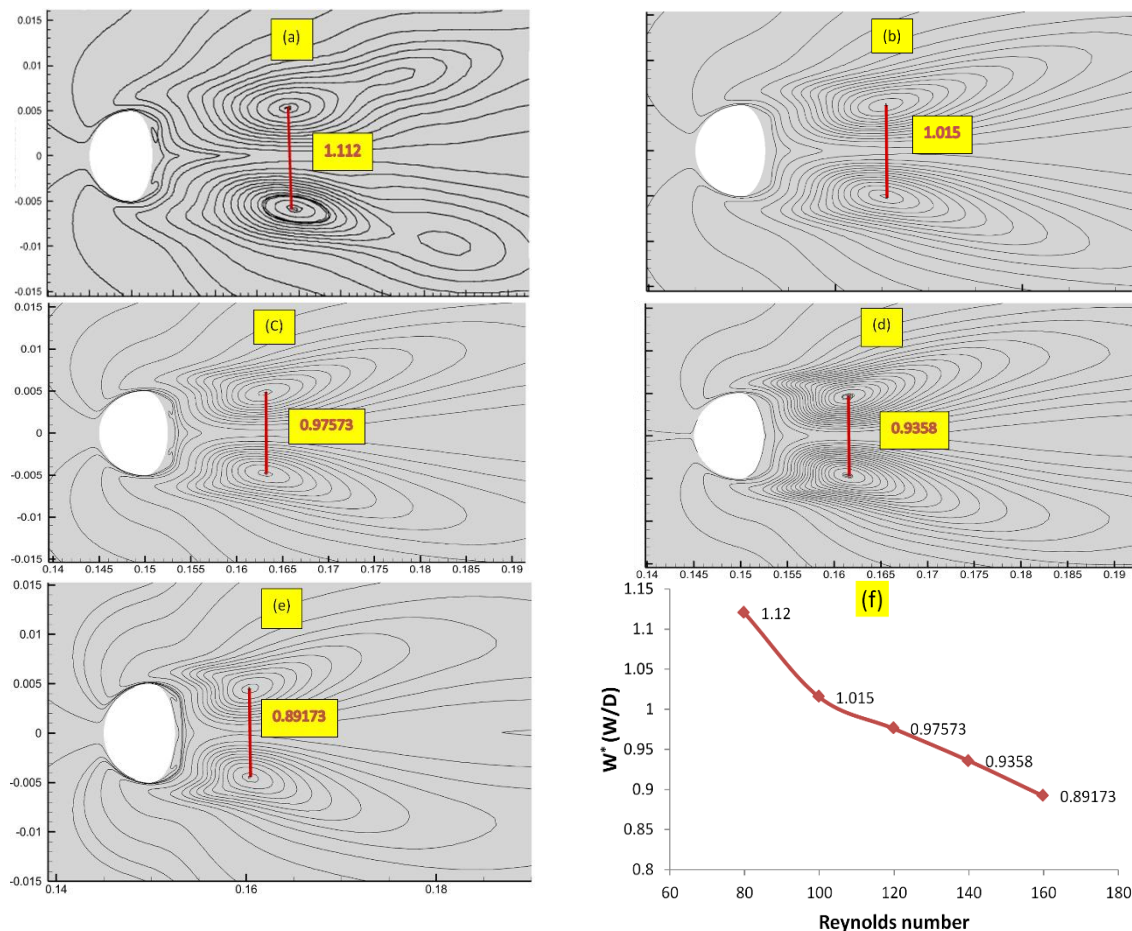


Fig. 5. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 0.5 at Reynolds number: (a)80, (b)100, (c)120, (d)140 and (e)160 domain scaling done-1:100. (f) Graph W^* versus Reynolds number for the S.F. 0.5

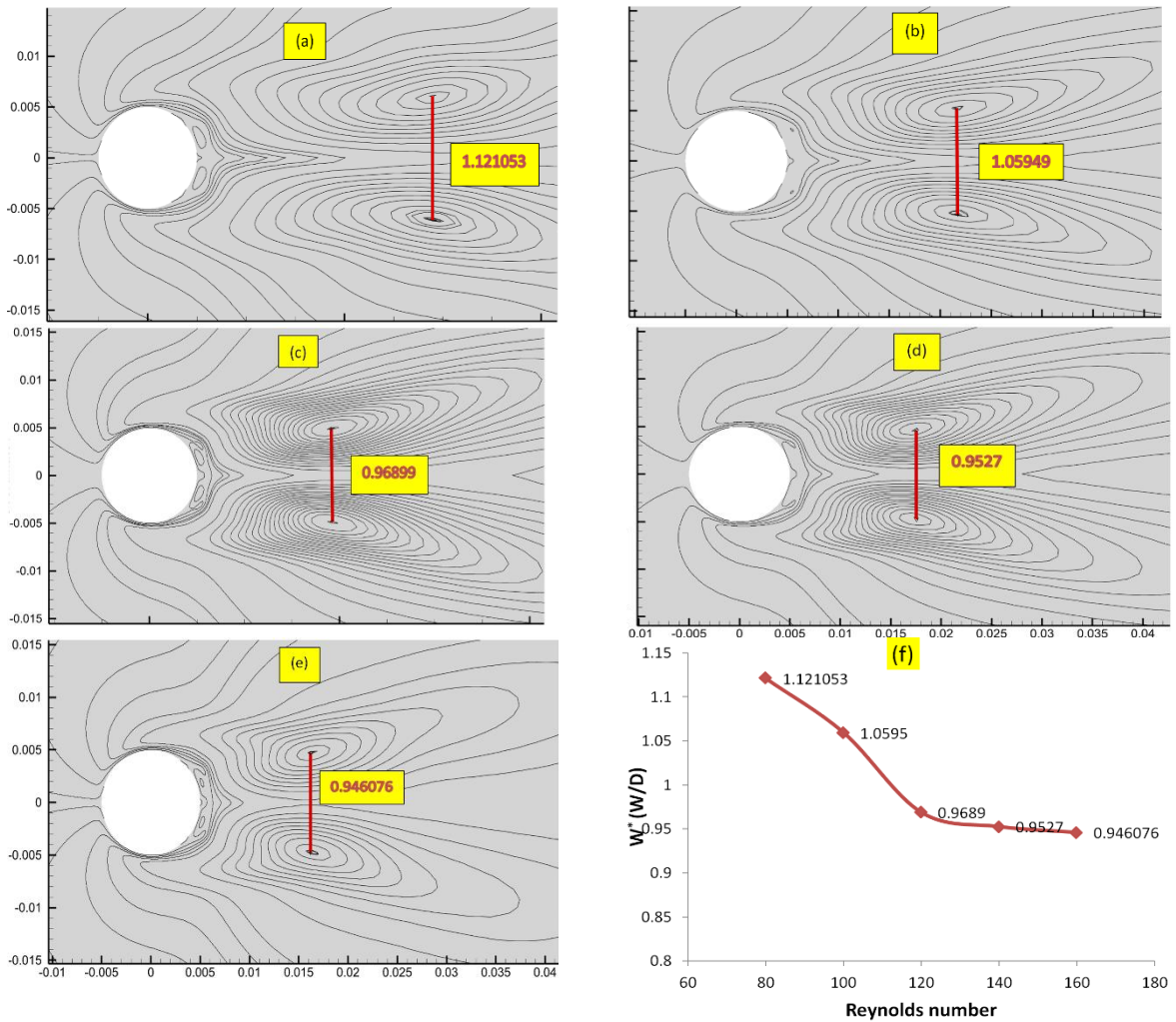


Fig. 6. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 1.0 at Reynolds number: (a)80, (b)100, (c)120, (d)140 and (e)160 domain scaling done-1:100. (f) Graph W^* versus Reynolds number for the S.F. 1.0

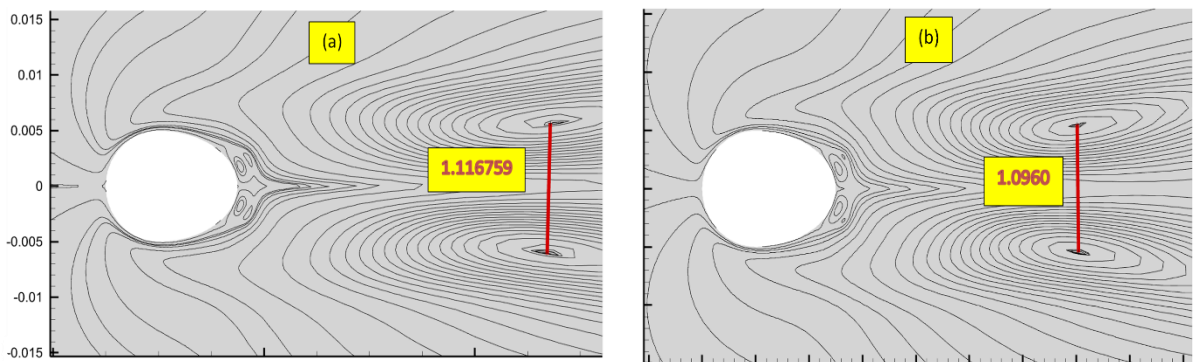


Fig. 7. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 1.50 at Reynolds number: (a)80, (b)100, (c)120, (d)140, and (e)160 domain scaling done-1:100. (f) Graph W^* versus Reynolds number for the S.F. 1.50

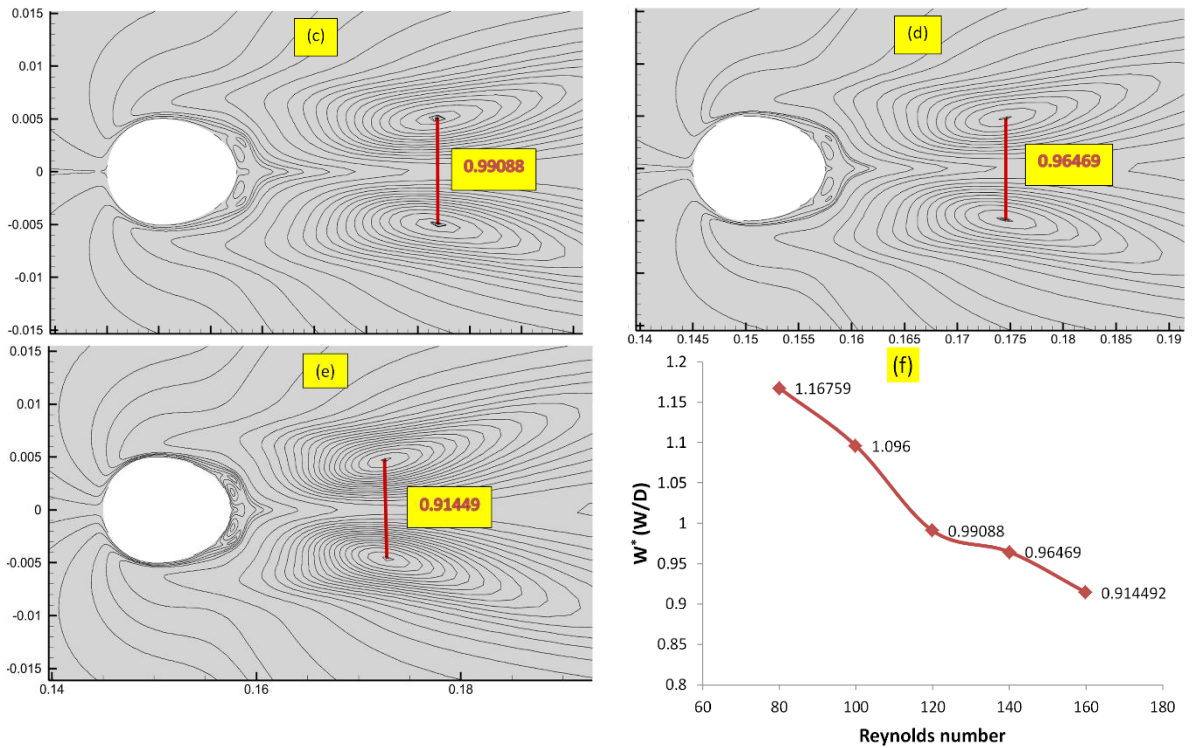


Fig. 7. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 1.50 at Reynolds number: (a)80, (b)100, (c)120, (d)140, and (e)160 domain scaling done-1:100.
(f) Graph W^* versus Reynolds number for the S.F. 1.50 (Continuous)

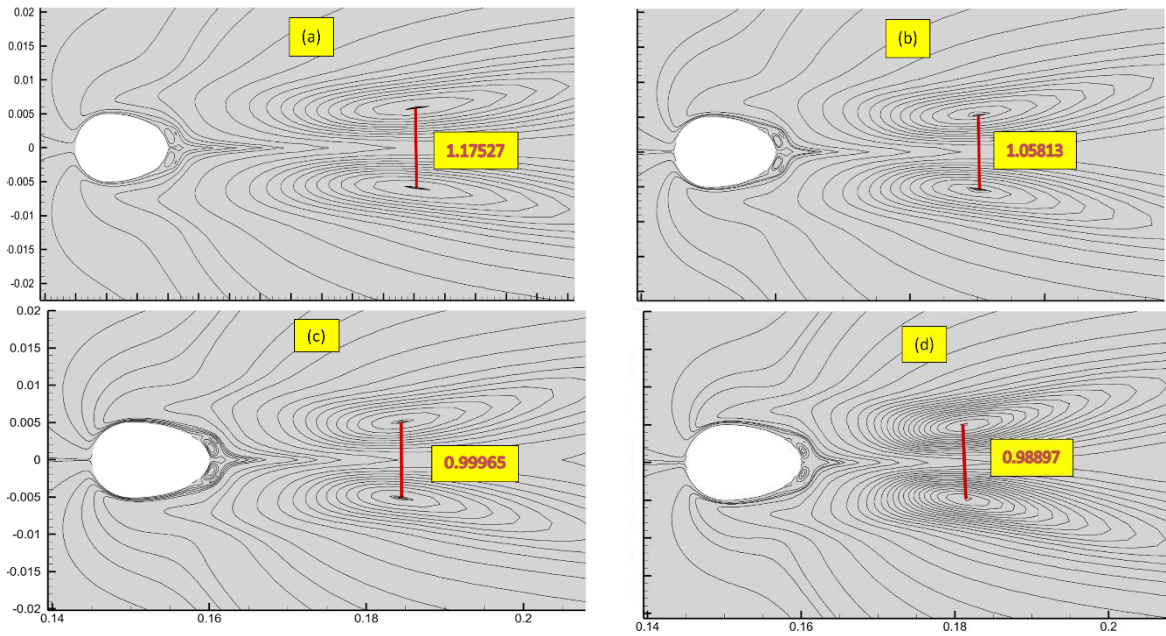


Fig. 8. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 2.0 at Reynolds number: (a)80, (b)100, (c)120, (d)140 and (e)160 domain scaling done-1:100.
(f) Graph W^* versus Reynolds number for the S.F. 2.0

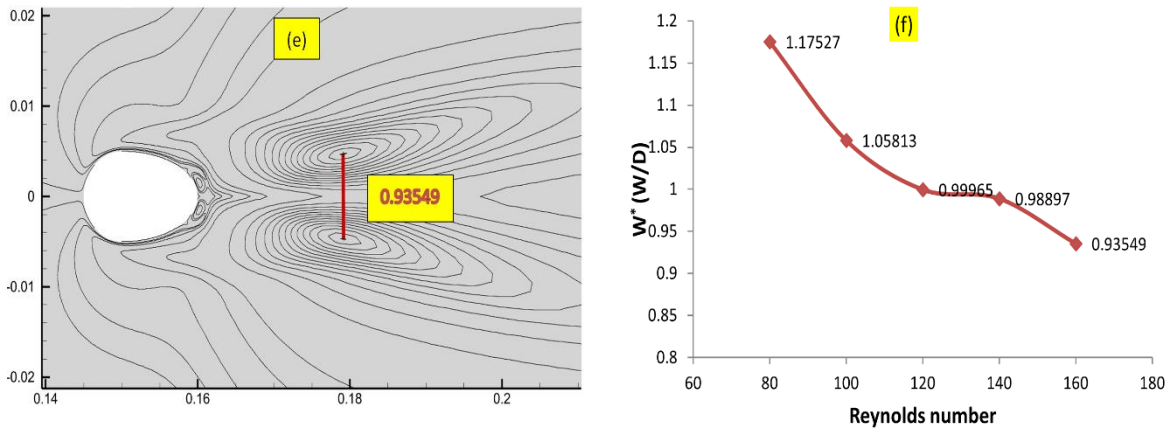


Fig. 8. Contours of time-average fluctuating velocity for the Shape Factor (S.F.) 2.0 at Reynolds number: (a)80, (b)100, (c)120, (d)140 and (e)160 domain scaling done-1:100. (f) Graph W^* versus Reynolds number for the S.F. 2.0 (Continuous)

The quantitative analysis with the corresponding graphs provided (Figure 9) reinforces the earlier observation of a non-intrusive effect of shape factor on wake width over the Reynolds number range. With geometric shapes that ranged from streamlined to bluff object bodies, the wake widths turned out not to significantly differ when compared at the same Reynolds number. This trend for the same shape case was true for all cases, further supporting the earlier conclusion that the Reynolds number was significantly more dominating than the geometry of the body for determining the wake characteristics in the laminar regime. A particularly interesting finding in this analysis was to observe that the wake width peculiarity for all configurations existed within the same order of magnitude as the projected length of the bluff body. In many cases, the projected length is close to or only slightly exceeds the wake width. Thus, indicating the wake spreading in the lateral direction possibly occurs due to inertial forces rather than shape-driven resistance. Overall, this learning increases the understanding of the possible wake development in the low to moderate Reynolds regimes; however, the shape factor provides a limited role in manipulating the fundamental scale of the wake characteristics.

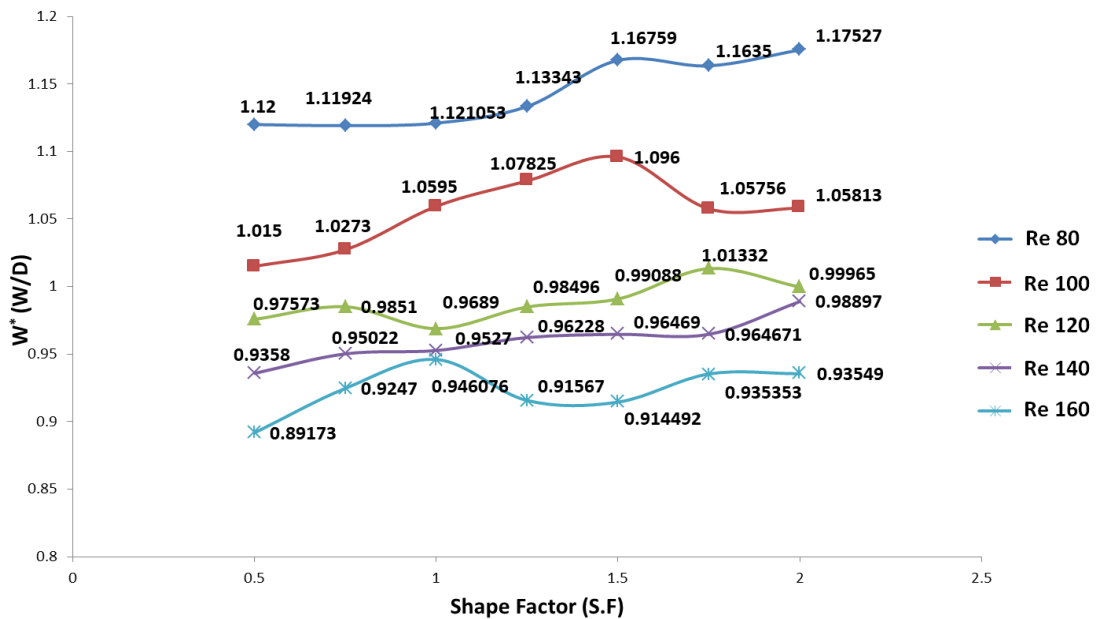


Fig. 9. Graph of varying non-dimensional wake width (W^*) versus Shape factors for the Reynolds number ranging 80-160.

4. Conclusions

This study focuses on the effect of streamlining, defined by the shape factor and the Reynolds number, on the wake width. For the purpose, the wake width is calculated over a range of shape factors, 0.5 to 2.0, at the laminar vortex shedding regime. The streamlining of a body is known to reduce both drag and lift, and the same applies to streamlining the rear part of the body. However, the effect of streamlining the rear part of the body appears to be non-intrusive to the wake width in the flow past a bluff body. Although the dominance of the Reynolds number on the wake width was established. The narrowing of the wake width on increasing the Reynolds number for all shape factors highlights the role of inertial forces in maintaining the wake structure. Moreover, the wake width is found to be somewhat on a similar scale to the projected length of the body (D). Thus, based on the study, it can be stated that bluntness alone cannot be considered a decisive parameter in determining the wake width.

Overall, this study provides insight into the physics behind bluff body wake dynamics at Reynolds numbers in the laminar vortex shedding regime. The insights can guide design choices for flow control, drag, and passive bluff body optimisation with the operating Reynolds number ranges.

Nomenclature

D	projected length or diameter of the base case, cm
W_d	wake width, cm
W^*	non-dimensionalised wake width (W_d/D)
ρ	density of fluid, kg/m ³
μ	dynamic viscosity, kgm ² /s
u'	stream-wise velocity fluctuations, m/s
u	streamwise velocity, m/s
$\overline{u}$	mean streamwise fluctuation, m/s
Re	Reynolds number
$S.F.$	shape factor

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