Effect of natural ventilation on the boundary layer separation and near-wake vortex shedding characteristics of a sphere

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Abstract Experiments were conducted in water and wind tunnels on spheres in the Reynolds number range $6 \times 10^5$ to $6.5 \times 10^5$ to study the effect of natural ventilation on the boundary layer separation and near-wake vortex shedding characteristics. In the subcritical range of $Re (< 2 \times 10^5)$, ventilation caused a marginal downstream shift in the location of laminar boundary layer separation; there was only a small change in the vortex shedding frequency. In the supercritical range ($Re > 4 \times 10^5$), ventilation caused a downstream shift in the mean locations of boundary layer separation and reattachment; these lines showed significant asymmetry in the presence of venting. No distinct vortex shedding frequency was found. Instead, a dramatic reduction occurred in the wake unsteadiness at all frequencies. The reduction of wake unsteadiness is consistent with the reduction in total drag already reported. Based on the present results and those reported earlier, the effects of natural ventilation on the flow past a sphere can be categorized into two broad regimes, viz., weak and strong interaction regimes. In the weak interaction regime (subcritical $Re$), the broad features of the basic sphere are largely unaltered despite the large addition of mass in the near wake. Strong interaction is promoted by the closer proximity of the inner and outer shear layers at supercritical $Re$. This results in a modified and steady near-wake flow, characterized by reduced unsteadiness and small drag.

1 Introduction

Several methods have been used in the past to reduce the drag of 2-D and 3-D bluff bodies. Reviews by Zdravkovich (1981) and Viswanath (1994) give a wide coverage of the various passive techniques and their limitations in the context of 2-D and axisymmetric bases in different speed regimes. In contrast to 2-D bodies, very little is understood on the general features of the near-wake structure of 3-D bodies except that vortex shedding is less intense, as discussed in Mair and Maufl (1971). In earlier studies by Suryanarayana et al. (1993) and Suryanarayana and Meier (1995), attempts were made to understand some of the major aspects of the near-wake structure of a sphere (which represents an idealized 3-D bluff body) and to control the same for drag reduction using natural/passive ventilation. Natural ventilation of a sphere involves interconnecting the stagnation zone and the base through an internal cylindrical duct. As a result of the pressure difference, a natural bleed occurs into the near wake. Aspects of drag reduction, flow-field visualization and surface pressure distributions with and without natural ventilation have already been published. As reported therein, ventilation causes a large reduction (65%) in total drag for supercritical Reynolds numbers ($> 4 \times 10^5$) due to strong interaction between the separated external flow and the vent flow, promoted by their close proximity. The reduction in drag was shown to be caused by substantial base pressure recovery. At subcritical $Re (< 2 \times 10^5)$, there was a marginal change in the total drag. Visualizations of the near wake in the supercritical Reynolds number ($Re$, based on diameter $D$) regime indicated that ventilation leads to modification/suppression of the randomly rotating vortex structure, which is known to be associated with the unvented sphere.

As shown by the early experiments of Wieselberger and Prandtl (1914), downstream shift of the location of boundary layer separation on a sphere causes a drag reduction. When the location is inferred from a finite number of pressure ports in an experiment, the result is an incomplete description, especially at supercritical $Re$ when the separation is non-axisymmetric. A global visualization of the external flow is more useful in such situations.

In the case of a circular cylinder, Roshko (1961) has shown that the total drag and Strouhal number of vortex shedding are closely related. Such a comparison for a sphere shows only a weak correlation. This leads one to speculate that vortex shedding, even at subcritical $Re$, may not be a very important feature of the flow past a sphere as far as the mean-flow dynamics in the near wake is concerned. Such a suggestion has been made by Viswanath (1994) in the context of low-speed axisymmetric base flow at relatively high $Re$. In 2-D bluff-body flows, any passive or even energetic technique used for drag reduction leads to a decrease in the stability of the base region. It is interesting to note that this is not the case for 3-D bodies.
In the light of the above, the present experiments were undertaken to study the gross features of boundary layer separation and reattachment as well as near-wake vortex shedding for the flow past a sphere with and without ventilation. The focus of the study is the effect of venting at supercritical $Re$ when ventilation reduces the total drag by 65% of the basic value. Hence, the identical sphere model which was used in drag measurements (Suryanarayana et al. 1993) was used for the present investigations also. In this paper, the results on the basic or unvented sphere are first reported along with the data available in the literature on spheres. The changes caused by natural ventilation are discussed separately.

2 Experiments

Experiments were conducted in a water tunnel (test section size 0.25 m x 0.33 m) at the DLR Institute for Experimental Fluid Mechanics, Göttingen, Germany, and in a wind tunnel (test section size 1.5 m x 1.5 m) at the National Aerospace Laboratories (NAL), Bangalore, India, covering a wide range of $Re$ from $6.0 \times 10^3$ to $6.5 \times 10^5$. The free-stream turbulence intensities in the tunnels are about 0.5% and 0.12%, respectively. A vertically supported wooden sphere 79 mm in diameter, as shown in Fig. 1a, was used in the water tunnel at DLR in the range $6.0 \times 10^3 < Re < 6.5 \times 10^5$. The sphere was held symmetrically, as shown in Fig. 1b, using a sting 10 mm in diameter. Vent holes of diameter ($D_{vent}$) 12 mm and 30 mm were drilled on the respective spheres across the stagnation region to the base region to provide a vent area ratio $A_v$ of 2.25% ($= D_{vent}^2/D^2$). Figure 1c shows a photograph of the model mounted in the test section of the wind tunnel at NAL. A detailed discussion on support interference effects, justifying the use of an asymmetric support in the wind tunnel is given in Suryanarayana (1996).

Surface-flow visualization experiments were carried out to estimate the mean locations of boundary layer separation and reattachment. A mixture of titanium dioxide, oleic acid, and oil was used for this purpose. A hot-film probe in the water tunnel and a hot-wire probe in the wind tunnel were used to measure the $u'$ fluctuations in the near wake. The probe was located at several locations in the near wake of the sphere models.

3 Results and discussion

3.1 Boundary layer separation characteristics - unvented sphere

Figures 2a and b show typical surface-flow patterns obtained at $Re = 6.5 \times 10^4$ and $6.5 \times 10^5$ in the wind tunnel.
determined through skin-friction measurements reported by Achenbach (1972) and surface pressure measurements by Fage (1936) are also included. Typical uncertainty bands, as mentioned by the individual authors, are also marked. As may be expected, a certain degree of uncertainty is inherent in inferring the separation and reattachment lines in each technique employed. For example, the locations inferred from surface-flow patterns (as done now) could have an error of ±2–3 mm, which would translate into a corresponding percentage error in the location depending on the sphere diameter. The uncertainty band at higher Re is inherently high because of skewness. The minimum and maximum variation (as much as 10°) from the mean is considered as the uncertainty band, as also done by Taneda (1978). Dissimilarities in the supports used, their interference on the flow and different free-stream turbulence intensities in different sets of experiments also contribute to scatter in the data.

It is evident from Fig. 3 that excellent agreement exists among the different sets of data in the subcritical regime, including the curve fit \( \theta_s = 78 + 275 \Re^{-0.37} \) recommended by Clift et al. (1978). As the critical regime is approached, the separation location rapidly shifts downstream; the limited data available in the literature suggest that the laminar separation location may settle around 100° to 110° towards the end of the Reynolds number range.

Figure 4 shows the variation in the transitional/turbulent bubble reattachment position with Re. The results clearly show that the separated shear layer does not reattach on the sphere (and hence no separation bubble) for \( \Re < 2 \times 10^5 \) (the shear layer closure occurs in the near wake). As Re is increased, the bubble reattachment position also shifts downstream in the critical regime, in accordance with the movement of \( \theta_s \) and appears to settle down to a value around 115° at supercritical Re. The present data clearly show that the reattachment location moves upstream (by a few degrees) before moving downstream in the critical regime.

The location of turbulent boundary layer separation is shown plotted in Fig. 5 as a function of Re. The present results show a gradual downstream shift of \( \theta_{lb} \) with Re, similar to those of \( \theta_s \) and \( \theta_{bs} \) and appears to settle around a value of \( \theta_{lb} \approx 155° \). On the other hand, the data of Achenbach (1972) exhibit a nearly constant value (around 120°), which may be due to the high free-stream turbulence intensity in his (0.45%) as compared with the present (0.12%) experiments; also, this value may represent the asymptote higher Re.

The location of laminar boundary layer separation is shown plotted in Fig. 5 as a function of Re. The present results show a gradual downstream shift of \( \theta_{lb} \) with Re, similar to those of \( \theta_s \) and \( \theta_{bs} \) and appears to settle around a value of \( \theta_{lb} \approx 155° \). On the other hand, the data of Achenbach (1972) exhibit a nearly constant value (around 120°), which may be due to the high free-stream turbulence intensity in his (0.45%) as compared with the present (0.12%) experiments; also, this value may represent the asymptote higher Re.

1.2 Vortex shedding

Typical p-components of water and respectively existences \( \Re \leq 2.6 \times 10^4 \), 1.9 Hz set at the height Durbin this peak noise in the frequency up to 8000 is observed in water.
example, (as done in the literature), as 10° range. If/turbulence is not readily observable in the near stagnant position, in accordance with the location of bubble reattachment on unvented sphere with data in the literature

Fig. 4. Comparison of the location of bubble reattachment on unvented sphere with data in the literature.

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Fig. 6. Typical power spectra of $u'$ fluctuations behind the unvented sphere in water tunnel

Fig. 7. Typical power spectra of $u'$ fluctuations behind the unvented sphere in wind tunnel

As indicated in Fig. 10, the surface-flow features at supercritical $Re$ exhibit greater axisymmetry and a downstream shift ($\approx 5^\circ$) in the locations of $\theta_1$, $\theta_2$, and $\theta_3$. The improved symmetry of the flow is associated with the stabilization of the 3-D randomly rotating horseshoe vortical structure by natural ventilation, as observed on a laser light sheet by Suryanarayana et al. (1993). The effects of ventilation on composit...
Figs. 9a, b. Effect of ventilation on external flow separation at subcritical Re: a unvented sphere, \( Re = 6.5 \times 10^4 \); b vented sphere, \( Re = 6.5 \times 10^4 \)

Figs. 10a, b. Effect of ventilation on external flow separation at supercritical Re: a unvented sphere, \( Re = 6.5 \times 10^5 \); b vented sphere, \( Re = 6.5 \times 10^5 \)

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subcritical regime. It is clear that there is only a small change in the vortex shedding frequency in the presence of ventilation. Figure 14 shows the variation in the Strouhal number with \( Re \) in the range of \( 6 \times 10^3 \leq Re \leq 2.6 \times 10^5 \).

In the supercritical regime where a significant reduction in total drag (65%) was observed by Suryanarayana et al. (1993), the power spectral density plots at \( Re = 4.8 \times 10^5 \) (Fig. 15) and at \( Re = 6.5 \times 10^5 \) (Fig. 16) show a remarkable reduction in the amplitudes at all the frequencies. This feature was observed at several vertical stations within the near wake. The spectra do not show any peak frequency in the presence of ventilation, which is not surprising, since vortex shedding does not exist even in the absence of venting.

It is therefore clear that the observed drag reduction is associated with a significant reduction of wake unsteadiness, presumably caused by the stabilisation/weakening of the randomly rotating 3-D vortical structure of the unvented sphere. The spectra also suggest a more steady boundary layer separation with ventilation. Interestingly, Quadflieg's (1975) experiments involving drag measurements on a sphere show evidence of drag reduction associated with steady separation of the boundary layer and quietening of the near wake. The steady separation was achieved by placing a thin wire close to the location of turbulent boundary layer separation.

Figure 17 shows a comparison of the time-averaged flow pattern of the near wake with and without ventilation, taken from Suryanarayana et al. (1993) and Taneda (1978).
Fig. 14. Effect of ventilation on wake Strouhal number

Fig. 15. Effect of ventilation on power spectral density of $u'$ fluctuations in the near wake at supercritical $Re (4.8 \times 10^5)$

Fig. 16. Effect of ventilation on power spectral density of $u'$ fluctuations in the near wake at supercritical $Re (6.5 \times 10^5)$
The effects of natural ventilation on the flow past spheres can thus be grouped in two broad categories, viz., weak and strong interaction regimes, as schematically described in Fig. 18. The interaction is weak in the subcritical Re regime, probably because of the early separation ($\theta_{ls} \approx 80^\circ$) of the boundary layer, which results in a relatively larger distance between the inner and outer shear layers. The basic features of the unvented sphere such as the mean separation characteristics, base pressure, and vortex shedding frequency are therefore largely unaltered, despite the large addition of mass in the near wake. The strong interaction regime is characterized by a delayed separation ($\theta_{ls} \approx 155^\circ$), which reduces the distance between the inner and outer shear layers. The boundary layer separation is more steady, resulting in a dramatic reduction in wake unsteadiness, improved base pressure recovery, and notable drag reduction.

4 Conclusions

Experiments were carried out to assess the effect of natural ventilation on boundary layer separation and near-wake vortex shedding characteristics of spheres in the Reynolds number (Re based on diameter) range $6.0 \times 10^3$ to $6.5 \times 10^5$ in water and wind tunnels. In the subcritical regime of Re, ventilation caused a downstream shift in the location of laminar boundary layer separation and a small change in the vortex shedding frequency, consistent with the small change in total drag, as reported by Suryanarayana et al. (1993). In the supercritical Re regime, ventilation caused a downstream shift in the mean locations of laminar boundary layer separation, transitional/turbulent shear layer reattachment and turbulent boundary layer separation; the lines showed significant asymmetry due to venting at supercritical Re. Hot-wire measurements in the near wake indicate absence of a distinct vortex shedding frequency; the spectra of $u'$ signals show a dramatic reduction in the wake unsteadiness at all frequencies across the near wake in the presence of venting. The reduction in wake unsteadiness is consistent with the large reduction in total drag already reported in...
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