Experimental Investigation of the Flow Structure around a Sphere and Its Control with Jet Flow via PIV

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Abstract—The flow characteristics of a smooth sphere and a vent sphere located in a uniform flow for the Reynolds number range 2500≤Re≤10,000 are studied quantitatively using the particle image velocimetry technique and qualitatively with dye visualization. The flow phenomena in the downstream regions of the sphere increase the instability of the vortical flow structure significantly. The present investigation concentrates on the characterization of the flow structures using the time-averaged and instantaneous flow data in a plan view at laser sheet location passing through the sphere equator. Distributions of velocity vectors, patterns of streamlines and vorticity contours characterize the flow structure, in detail. It is observed that the modified flow structure of the near wake of the vented sphere may be characterized by a pair of counter-rotating ring vortices, which have the effect of aerodynamically streamlining the sphere. The obtained results can be helpful for developing and validating numerical predictions as well as designing.

Keywords—Flow control, Instability, PIV, Sphere, Vorticity, Turbulence, Vortex shedding, Wake flow

I. INTRODUCTION

Flow structures in the downstream of a single sphere are encountered so frequently in various industrial applications such as various multiphase flow system, air pollution, nuclear and thermal power plants, pneumatic and hydraulic conveying, chemical and food processing, combustion systems, sport balls and bomb. Large amount of researches have been conducted flow around a sphere for different Reynolds number and massive amounts of data for vortex shedding frequency, pressure coefficient, drag and lift force coefficients have been accumulated as cited in the references and cited therein. However, at moderate Reynolds numbers such as 2,500≤Re≤10,000 due to lack of data under various conditions, more work is required to fully understand the effects of the smooth and vented sphere.

Some of studies on flow characteristics and control around sphere and other bluff bodies were given and cited therein [1-25]. None of these studies have not been compared the flow structure around a smooth and vented sphere using PIV technique.

II. EXPERIMENTAL SETUP

Experiments were performed in a large-scale open water channel with a test section length of 8000 mm and a width of 1000 mm at the Department of Mechanical Engineering at Cukurova University, Turkey. To perform the present experimental study, the test section made from 15 mm thick transparent Plexiglas sheet, which had a total height of 750 mm, was filled with water to a level of only 450 mm. Before reaching the test chamber, the water was pumped into a settling chamber and passed through a honeycomb section and a two-to-one channel contraction. An overview of experimental system of the sphere is shown in Fig. 1. Free stream turbulence intensity of the flow is less than 0.5% in the range of the present Reynolds numbers, Re = (U∞D)/v, based on the sphere diameter (D). Here, v and D are kinematics viscosity and diameter of the sphere (D), respectively. U∞ is free stream velocity taken as 117.6 mm/s. The sphere with a diameter of 42.5 mm was made of Plexiglas so that the laser light propagates easily from them. In addition, water cell segment of the sphere equator with a diameter of 38.5 mm and a wall thickness of 2.0 mm was created. It was filled with distilled water and had a total height of 8 mm in order to reduce largely the laser light deflection on the sphere. The sphere surface was highly polished to avoid effects of surface roughness. The laser sheet was located at 225 mm above the bottom surface of the channel while the water height hw was 450 mm in all cases. To support the sphere in the water channel, a circular bar with a 5 mm diameter was connected to the sphere from the top. Disturbance effect of the support bar on the laser sheet location of the measurement plane that was observed by dye injection was negligible in the consideration of support diameter with respect to the sphere diameter. The solid blockage ratio of the sphere including support was 1.3 %. Sphere models are presented in Figure 2b. The vented sphere made of solid plexiglas and did not permit to pass the laser light. The ratio of the smooth sphere diameter...
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(D=42.5 mm) to vented hole diameter (d_{hole} = 6.4 mm) is d_{hole}/D = 0.15, which provides a vent area of 2.26%.

An interrogation window of 32x32 pixels in the image was selected and converted to grid size approximately 1.44x1.44 mm² for the single sphere (0.034DX0.034D). The overall fields of physical view were for both spheres, yielding to 7,227 (99x73) velocity vectors for whole taken images. During the interrogation process, an overlap of 50% was employed in order to satisfy the Nyquist criterion. Patterns of instantaneous particle images with a total of 350 images for a continuous series were taken at the rate of 15 Hz, thereby spanning 23.27 sec. Averaged patterns of the flow structure were calculated from all of the instantaneous images. The laser sheet was generated from a dual pulsed Nd:YAG system, having the maximum output of 120 mJ per pulse, which had time delays \( \Delta t = 1.0 - 1.7 \text{ ms} \) for the present experiments. Inappropriate displacement vectors caused by shadows, reflections, or laser sheet distortions in the flow field replaced by using bilinear interpolation between surrounding vectors in the post-processing step. This algorithm included magnification factor and image captured rate to calculate velocities from the valid vectors. The field was then smoothed by a Gaussian weighted averaging technique. To minimize distortion of the velocity field, a smoothing parameter of 1.3 was chosen. After having been vector field, the vorticity patterns of the wake flow were determined from the velocity field using a finite difference scheme with an in-house software. The details of the effects of these factors can be found in the studies of Hart [26], Fouras and [27], Westerweel [28] and Adrian [29]. The factors contributing to uncertainty in the velocity measurement using the PIV technique were critically assessed by Westerweel [28] concluding that uncertainty estimation in the velocity measurement was less than ±2%.

III. RESULTS AND DISCUSSION

Figures 2a and 2b show typical visualization images of instantaneous flow fields around a smooth sphere and a vented sphere for 5,000 in which dye ports with 0.7 mm diameter are located on equator of the sphere at angle values with respect to the flow direction as 0°, 70°,90°, 110°, 180°, 290°, 270° and 250°. Dye visualization representative images are presented with two different images to show evolution and progress of the small scale vortices designated by A to H. The separated and recirculating flow in the near-wake region with the help of visualizing are clearly seen for the sphere with laser illumination using the Rhodamine dye injection technique in the near wake region. Small scale vortices around the wake region are formed around larger vortices with a wavy appearance due to Kelvin Helmholtz instability. Formation of the spiral vortices begins to occur in the very close region of the sphere. As the flow travels in the downstream direction, the dimensions of the vortices increase around the bluff body. Then these vortices are shed from the periphery of the sphere directly to the inward wake region. The large eddies are formed at a regular frequency, and they produce pressure disturbances in the flow. The flow patterns in Figs. 2a and b show that the laminar boundary layer separates at around \( \theta = 85° \pm 5° \) for the present Reynolds number range, where \( \theta \) is measured from the front stagnation point. Shedding shear layer
becomes unstable due to the Kelvin-Helmholtz instability caused by the large velocity difference at the interface between the free-stream and sphere wake flow regions. Thereafter, the laminar shear layer turns into a powerful turbulent flow structure. Several vortex-ring shaped protrusions appear as an indication of the shear-layer instability along the borders between the wake and free stream regions, as also observed by Jang and Lee [5].

in a wavy form in the wake region for both spheres as seen in Fig 2. Shear layers emanating from the both side of the sphere merge at a location approximately two sphere diameter (2D) from the central point of the sphere and instability rises after this point as seen in Fig 2. The vortices generated by the shear-layer instability travel downstream and eventually compose a large-scale waviness of vortical structures in the wake. These instabilities and disorderness in the flow retain further downstream in the free stream flow direction having an “S” form like von Karman vortex streets approximately after a distance of 2.5D from the central point of the sphere.

Figures 3 and 4 show comparison of instantaneous velocity fields $V$ and $\omega^*$ around the smooth sphere (left column) and vented sphere (right column) for $2500<Re<10,000$. Instantaneous vorticity contours of the wake structure is normalized as $\omega^*$ (i.e., $\omega^* = \omega D / U_\infty$). All figure dimensions are normalized with the sphere diameter designated as $x/D$ and $y/D$. Even though small-scale Kelvin Helmholtz’s vortices are clearly shown for dye visualization results, PIV results display more rounded vortices. However, numerous eddy vortices occur due to the three dimensional and complex flow structures. Jet flow through the ventilation hole make the flow structure more symmetric and increase the fluctuations in the base region of the sphere. The vortices produced from the flow separation around the periphery of the sphere have a tendency to move inwards because of the lower pressures prevailing within the wake. This situation is counter-balanced by the growing wake size, which shifted the vortex centerline outwards. Regarding the onset and development of small-scale vortical structures in the separating shear layer, regions of low-level vorticity concentration are discernible in the pattern of instantaneous vorticity for all patterns.

The wake region accommodates velocity vectors with very small magnitude in the downstream region of the smooth and vented sphere, which are the source of small-scale secondary vortices, as seen in Fig. 3. The streamwise separation of successive vorticity peaks in the near wake region for the smooth sphere is larger than that for the vented one. The flow is three-dimensional, and shedding vortices convey fresh fluid into the wake flow region, magnifying the entrainment processes, which occurs with higher order of magnitude for the vented sphere. However, it is clear that there is only a small change on the flow patterns in the presence of ventilation. On the other hand, Suryanarayana and Prabhu (2000) stated that the observed drag reduction of wake unsteadiness, presumably caused by the stabilization/weakening of the randomly rotating 3-D vortical structure of the smooth sphere, which was also observed in the present study. As seen in Fig 4, secondary vortices forms in the wake region due to jet flow through the vent. It may be noted that any reduction in the wake unsteadiness may be expected to result in drag reduction. The modified flow structure of the near wake of the vented sphere may be characterized by a pair of counter-rotating ring vortices, which have the effect of aerodynamically streamlining the sphere as expressed by Suryanarayana and Prabhu (2000).
In the present study, the Reynolds number range is limited due to restriction of free stream flow velocity in the water channel and system capability. Therefore, all experiments were performed at the subcritical Re. As pointed by Suryanarayana and Prabhu (2000), the effect of natural ventilation can be categorized in two broad regimes as weak and strong interaction regimes. At subcritical Reynolds number (Re<4×10^5), the weak interaction regime occurs and the broad features of the basic unvented sphere are largely unaltered despite the larger addition of mass in the near wake. Strong interaction is promoted by the closer proximity of the inner and outer shear layers at the supercritical Re, which results in a modified/weakened and steady near-wake flow characterized by reduced unsteadiness.

Comparison of time-averaged streamline topology <Ψ> around the smooth sphere (left column) and vented sphere (right column) for 2,500≤Re≤10,000 is displayed in Fig 5. The junction point of the streamlines separated from the surface of the sphere is denoted with “S”. This junction point is called as Saddle point S which shows the merging point of the shear layers emanating from both sides of sphere. Locations of foci designated with “F1 and F2” that are rolling in the clockwise and in counter clockwise direction on with respect to the sphere central axis exhibit well-defined critical points. It can be concluded that the flow around spheres is three dimensional. The time-averaged streamline pattern shapes extended upstream to near base region of the body are elliptical and have a limited spiral cycle. Comparison of the time-averaged patterns shows that flow structures of the wake are almost equally symmetrical with respect to the centerline of the smooth and vented sphere. As the Reynolds number increases, saddle point S1 becomes closer to the base of the sphere due to the increased momentum transfer. For smooth sphere case, two foci F1 and F2 occur while flow structure of the vented sphere case exerts four foci as F1, F2, F3 and F4 due to the jet flow through the ventilation hole.

The effective length of the jet flow decreases with increasing the Reynolds number. Two saddle points S1 and S2 for the vented sphere case occur owing to the presence of jet flow. The saddle point on the time-averaged streamline topology generally forms later for the vented sphere for all Reynolds numbers. For example, at Re=5,000, the non-dimensional wake lengths (L/D) measured from the base of the sphere to the saddle point S1 in the averaged streamline topology <Ψ> are approximately 1.15D and 1.22D for the smooth sphere and vented sphere, respectively.
Figure 5. Comparison of time-averaged streamline topology $\langle \Psi \rangle$ around the smooth sphere (left column) and vented sphere (right column) for $2500 \leq Re \leq 10,000$.

Figure 6. Comparison of Reynolds stress contour correlations $\langle u'v'/U_{\infty}^2 \rangle$ around the smooth sphere (left column) and vented sphere (right column) for $2500 \leq Re \leq 10,000$.

**IV. CONCLUSIONS**

The flow structure in the downstream region of a smooth sphere and vented sphere for $2500 \leq Re \leq 10,000$ was investigated using a PIV and dye techniques in a circulating open water channel. The following results are derived:

Small and large-scale waviness of vortical structures occur in the wake region of the sphere in the streamwise direction. The formation of these small and large-scale waviness of vortical structures is assessed to be closely associated with the temporal evolution of vortices generated by the shear-layer instability. It is observed that the shedding location of the large-scale vortices rotates slowly and irregularly, and they rotate at random about the streamwise axis when they travel downstream for both smooth and vented spheres. It is observed that the wake is unstable with vortex shedding. The mean velocity field showed two peculiar large-scale recirculation vortices downstream of the sphere model, and the length of the circulation region was approximately one diameter in the wake region for the spheres.

The PIV results for the instantaneous velocity fields of the smooth and vented spheres show an unsteady vortex formation mechanism. The PIV results of time-averaged turbulent
structures are consistent with the visualized flow field showing the onset of shear layer instability. Time-averaged and instantaneous flow data reveal that the size of the structure of the turbulent flow, the size of wake flow region, the location of singular and double points, the peak values of turbulence quantities as a function of Reynolds numbers. As observed by dye visualizations, flow structures from the vented sphere exhibit more parallel vortex streets that keeps their form without combination in downstream direction. The shear layer surrounding the recirculation bubble behind the sphere has a region of intensified velocity fluctuations with higher values of the Reynolds stress correlations than the vented sphere because of the three-dimensional vortex interactions. However, the concentration of small scale vortices (eddies) is more dominant in the wake of the vented sphere than that of the single sphere.

The instantaneous vorticity fields reveal an unsteady wavy structure of the wake sphere. The vortical flow structure in the near-wake region of the sphere show an unsteady behavior and the onset of shear-layer instability. The appearance of the unsteadiness in the wake sphere could be the result of instability of the two streamwise counter-rotating vortices. Because of the jet flow through the ventilation hole at the sphere center, the wake region of the sphere becomes more symmetrical. Mass and momentum transfer due to the jet flow provides fresh flow in the wake region of the sphere. Because of variation of flow structure with time, the flow structure downstream of the sphere has an unsteady motion. The modified flow structure of the near wake of the vented sphere can be characterized by a pair of counter rotating ring vortices, which have the effect of aerodynamically streamlining the sphere. Experimental data obtained in this study will enhance our understanding of the smooth and vented sphere wake characteristics to develop a strategy for the validation of numerical models and design in the future.

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