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Investigation of flow characteristics around a sphere placed in a boundary layer over a flat plate

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ABSTRACT

Flow characteristics around a sphere located over a smooth flat plate were experimentally investigated using dye visualization and PIV technique. The sphere was embedded in a turbulent boundary layer with a thickness of 63 mm which was larger than the sphere diameter of $D = 42.5$ mm. Instantaneous and time-averaged flow patterns in the wake region of the sphere were examined from the point of flow physics for different sphere locations in the range of $0 \leqslant G/D \leqslant 1.5$ where G was the space between the bottom point of the sphere and the flat plate surface. Reynolds numbers with a range of $2500 \leqslant \mathrm{Re} \leqslant 10000$ based on the free-stream velocity while the velocity distributions over the plate surface are the developed turbulent boundary layer condition attained by using a tripwire. Distributions of velocity fluctuations, patterns of sectional streamlines, vorticity contours, velocity fields, turbulent kinetic energy and corresponding Reynolds stress correlations are obtained using PIV data. It was found that a jet-like flow stimulated the flow entrainment between the core and wake regions as a function of the sphere locations. The gap ratio has a strong influence on the flow structure of the wake-boundary layer interaction and the variation of the reattachment location of the separated flow from the plate surface. The time-averaged flow patterns yield asymmetric structures downstream of the sphere due to the effect of the boundary layer flow distribution.

1. Introduction

Flow around a sphere has many engineering applications in single and two phase flows such as nuclear and thermal power plants, towed sonar, swimming bodies in the water, pneumatic and hydraulic conveying, chemical and food processing, conveying of sediments in the river, rain drops, submarine research vehicles, combustion systems and sport balls. The wake of a sphere in uniform unbounded flow condition has been studied extensively for several years because of its complex flow features and practical applications. In the nature and engineering applications surfaces of most structures are exposed to non-uniform incoming boundary layer flow due to the proximity of a wall. The spherical structure finds application in not only gas tanks, but also in artistic structures and some types of vehicles [1]. The presence of boundary layer flow over the plane wall introduces significant complications into the wake of the sphere due to non-uniform velocity profile, gap flow between the bottom section of the sphere and plate surface and also occurrence of the vorticity field in the boundary layer region. When a sphere is immersed close to the wall, vortex shedding changes noticeably due to the influence of a non-uniform velocity profile which is formed as a result of boundary layer flow developed over the plane wall. This results in asymmetry in the strength of vortex shedding from upper and lower sides of the sphere and changes the direction of the mean force acting over the body away from the plane wall. The interaction between the turbulent wake of the sphere and the plane boundary layer is influenced by several factors such as approaching boundary layer thickness, free-stream disturbances, Reynolds number and gap flow between the sphere and plane wall. Therefore, a well-understanding of this kind of flows has crucial importance to choose or develop suitable flow control methods.

There are few studies around a sphere located in a boundary layer at intermediate Reynolds number. Tsutsui [1] performed a study related to interaction of boundary layer and a sphere in the wind tunnel to investigate flow around a sphere placed at various heights above a plane turbulent boundary layer at the Reynolds number 8.3×10^4 based on the sphere diameter. Okamoto [2] investigated the flow field of a sphere in contact with a plane and examined the wake structure and the aerodynamic force on the sphere. On the other hand, some of the studies for incoming uniform conditions were done experimentally and numerically. For example, Ozgoren et al. [3] performed an experimental investigation of flow structures downstream of a circular cylinder and

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sphere immersed in a free-stream flow for Re = 5000 and 10000 using qualitative and quantitative flow visualization techniques. They stated that the concentration of small scale vortices is more dominant in the wake of the sphere than that of the cylinder. Hassanzadeh et al. [4] carried out a numerical investigation of flow structures around a sphere at Re = 5000. As a preliminary study, Ozgoren et al. [5] investigated the flow-structure interaction of separated shear flow between the sphere wake and a flat plate and then they applied a passive flow control with a 2 mm o-ring located on the sphere surface at 55° with reference to the stagnation point at Re = 5000. They pointed out that the wake flow structure becomes symmetrical at smaller gap ratios and reattachment point on the flat plate surface occurs earlier. Jang and Lee [6] reported the vortical flow structures of the sphere wake in the streamwise plane at Re = 11000 in order to demonstrate flow structures and turbulence statistics. Leweke et al. [7] presented experimental visualization of flow structure in the wake of a sphere at Re = 320 and they observed periodic shedding of counter rotating of vortex filaments. Taneda [8] presented the wake configuration of a sphere and Sakamoto and Haniu [9] investigated the vortex shedding from spheres in a uniform flow. Achenbach [10] visualized the vortical structure of the sphere wake at Re = 1000 using dye and measured skin friction to investigate flow-separation angles in the range of Re = 10^5–10^6. Drag force around a stationary smooth sphere placed in a boundary layer type gradient flow for Reynolds numbers in the range of $3.62 \times 10^3 \leqslant Re \leqslant 6.45 \times 10^4$ was examined [11]. A series of experiments varying particle size, particle density, particle loading and the Reynolds number for particle-turbulence interaction in wall turbulent flows was conducted [12]. Moradian et al. [13] investigated experimentally the effects of free-stream turbulence intensity and integral length scale as free-stream turbulent parameters on the drag coefficient of a sphere in a closed circuit wind tunnel for Re = 22000–80000. They confirmed that the drag coefficient is decreased with increasing turbulence intensity. Also, Tyagi et al. [14] studied the effect of free-stream turbulence on the sphere wake and they found that the vortex shedding process downstream of the sphere was reduced when large organized motions were suppressed by the free-stream turbulence. Boundary layer interaction of two dimensional bluff body presents similar flow characteristics for the case of touching the wall surface. For example, a comprehensive review of Simpson [15] for cylinder reports several physical features of junction flows around bluff bodies such that, horseshoe vortices form in all types of bluff bodies' junction causing high rate of turbulent intensities, pressure fluctuations, circulatory motions and heat transfer rate around the bases of bluff bodies. Akoz et al. [16] experimentally investigated the characteristics of two dimensional turbulent flow around a horizontal wall mounted circular cylinder in the range of $1000 \leqslant Re \leqslant 7000$ based on the cylinder diameter. They reveal the mechanisms of vortical flow structure which mostly responsible for scour and burial process. In the heat transfer field, a sphere was available for the heat transfer enhancement on a plane, which was studied [17]. Prediction of flow and heat transfer around a body mounted on a surface is very important in relation to many of heat exchangers and fluid machineries [18–21]. Vortex shedding due to the scouring process causes additional unsteady forces such as lift and drag acting on the sphere. Consequently, the sphere becomes unstable and damages may occur on it. In order to prevent these problems, the flow structure around a sphere placed over the wall should be investigated, in detail.

In the present study, interaction of flow-structure between the separated shear flow emanating from periphery of the sphere and a flat plate is investigated using dye visualization and PIV technique for $2500 \leqslant Re \leqslant 10000$. The sphere locations from the flat plate surface vary in the range of $0 \leqslant G/D \leqslant 1.5$ to evaluate both the gap flow and boundary layer effects.

2. Experimental method and 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 the experimental system of the sphere is shown in Fig 1. The free-stream turbulence intensity of the flow is less than 0.5% in the range of the present Reynolds numbers, $Re = (U_\infty D)/v$, based on the sphere diameter. Here, v and D are kinematics viscosity and the diameter of the sphere, respectively. U_∞ is the free-stream velocity in the range of 59–236 mm/s. The sphere with a diameter of 42.5 mm was made of Plexiglas so that the laser light easily propagates through the sphere. The sphere surface was highly polished to avoid the effects of surface roughness. To fix the sphere in the water channel, a circular bar with a 5 mm diameter was connected to the sphere from the back surface of the sphere at the measurement plane in order to avoid support's effects while images were taken at the equator cross-section of the sphere. The disturbing effect of the support bar on the laser sheet location of the measurement plane that was observed by dye injection was

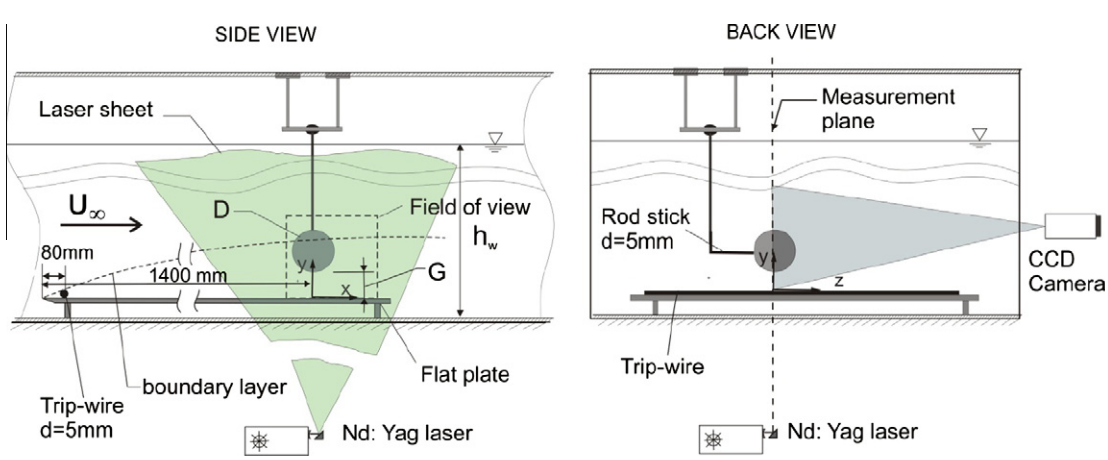

Fig. 1. Schematic view of the experimental setup of PIV system, laser illumination for a sphere located in a boundary layer.