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Shallow water experiments of flow past two identical square cylinders in tandem

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ABSTRACT

This study investigates experimentally the flow structure between two identical square cylinders as well as in the wake of downstream cylinder that are in-line positioned in tandem. The experiments are performed in a large scale water channel under shallow water conditions. Time-averaged streamline pattern as well as vorticity and turbulence statistics were calculated using Particle Image Velocimetry (PIV) measurement method for different gap ratios ($G/D = 0.5$ to $G/D = 5$, where G is the distance between the cylinders and D is the diameter of cylinder) between the cylinders at a fixed Reynolds number of 4470. The measurements were conducted for both side view and plan view configurations at Froude number $\mathrm{Fr} = 0.186$. The results obtained under shallow water conditions are compared with those obtained under deep water conditions by other researchers and it is found that, as explained in detail in the manuscript, the flow structures are remarkably different especially in the region between the two rectangular cylinders.

1. Introduction

The viscous flow past bluff bodies and the resultant vortex shedding have been studied experimentally and numerically in an extensive manner because of its numerous engineering applications. Periodic vortex shedding structures and fluctuating velocity fields in the vicinity of bluff bodies can cause structural damages due to periodic surface loading that also results in acoustic noise and drag. The configuration where a cylinder is placed in-line downstream of another cylinder is called a tandem arrangement. Flow over bluff bodies in tandem arrangement is an important engineering problem since this type of flow can be a model for flow around bridges, buildings, marine risers, heat exchangers, cooling systems for nuclear power plants, offshore structures, sea-bed pipelines and electronic devices. When two cylinders are placed in tandem, a complex flow structure is generated as a result of mutual interactions among the wakes behind the bodies.

While the flow past two circular cylinders in tandem has been studied in great detail, flow past rectangular and square cylinders, prisms, flat plates and other blunt cross-sections attracted the attention of researchers mostly in recent years due to their relevance to engineering applications and therefore, experimental and numerical studies about the flow past two square cylinders in tandem are relatively few. It is worth mentioning that the flow patterns and wake structures of the flow over square cylinder are quite different from that over a circular cylinder due to the fact that unlike the circular cylinder, the square cylinder tends to fix the separation point, causing differences in critical regimes; while also the separation mechanisms depending on the shedding frequencies and the aerodynamic forces differ significantly for the two geometries [1].

Due to relevance of tandem square cylinders to heat exchangers and cooling of electronic equipment, this flow geometry has been the subject of numerous experimental and numerical studies. Chatterjee and Amiroudine [1] carried out a two-dimensional numerical study to understand the effects of thermal buoyancy and Prandtl number on flow characteristics and mixed convection heat transfer from over two equal isothermal square cylinders placed in tandem arrangement within a channel in cross-flow at low Reynolds number. They found that the flow is completely steady for the chosen ranges of parameters. In a similar study, Sarkar et al. [2] performed a numerical study of mixed convective heat transfer from two identical square cylinders in a uniform upward flow at $Re = 100$ and they found that hydrodynamic instabilities grow and flow shows chaotic phenomena when the system is severely influenced by thermal buoyancy. Tatsutani et al. [3] conducted direct numerical simulation and dye visualization experiment of two-dimensional unsteady flow around two tandem

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square cylinders with different geometries in a channel and they found three different flow patterns depending on the separation ratio and Reynolds number. Rosales et al. [4] conducted a numerical study to analyze the unsteady flow field and heat transfer characteristics for a tandem pair of square cylinders in a laminar channel flow and they examined the drag, lift and heat transfer coefficients from the downstream heated cylinder due to in-line and off-set eddy promoting cylinders.

Studies concerning only fluid dynamics aspect and flow patterns in the vicinity of square cylinders in tandem have also been conducted by various researchers in both wind tunnels and water channels. Daloglu [5] performed an experimental study for cylinders in tandem in a square wind tunnel to determine the effect of Reynolds number and spacing between the cylinders on the pressure drop in the channel. The suppression of fluid forces acting on two square prisms in a tandem arrangement in which a flow approaching the upstream was controlled by a thin flat plate was examined experimentally in a wind tunnel by Alam et al. [6]. They found a dramatic decrease in fluid forces acting on both prisms for a certain range of control plate positions. In similar experimental studies, turbulent flow in the near wakes of single and tandem prisms [7], fluctuating [8] and time-mean and fluctuating [9] forces on two square prisms in a tandem arrangement were examined and lift, drag and Strouhal number of vortices shed from prisms were obtained for different spacing ratios between prisms. In two square section cylinders [10] and observation of hysteresis and flow characteristics around two square cylinders [11] are investigated experimentally. In the first one of these two studies, Luo et al. [10] obtained analytical expressions for the wake velocity distribution and for the correlation between wake half-width and downstream distance, which made it possible to estimate the wake velocity distribution without the availability of the actual experimental data. In the second study, Liu and Chen [11] report that hysteresis with two different jumps is present for all Reynolds numbers studied (2.0×10^3–1.6×10^4) when the spacing is varied in two different ways, one being a progressive increase and the other a progressive decrease. An experimental study of vortex shedding from two surface mounted cubes in tandem was conducted by Martinuzzi and Havel [12] who report that periodic shedding is triggered by the interference between a vertical flow stream along the front face of the downstream obstacle and the vortex in the inter-obstacle cavity. They also add that this three-dimensional mechanism is not observed for two-dimensional geometries and helps to explain why a locked regime cannot be observed for two square cylinders in tandem. A numerical study of vortex shedding in shear layer flow past tandem square cylinders in the vicinity of a plane wall, as well as vortical structures in the vicinity of the square cylinders was conducted by Bhattacharyya and Dhinakaran [13] for different flow parameters and spacing between cylinders. They found that the flow field is steady up to a critical Re and this critical Re depends on the spacing between two cylinders. They also report that the plane wall encounters unsteady separation when cylinders exhibit vortex shedding. A study on the phase lag between vortex shedding from two various shaped tandem bodies was conducted by Alam and Zhou [14] and its influence on fluctuating lift on upstream cylinder was analyzed. They developed a differential equation for phase lag (phi) and compared this equation with experimental data reporting that the agreement was well. Mean velocity field around prismatic bodies in tandem arrangement was measured in a wind tunnel and the effect of spacing between the bodies were inspected by Tulapurkara et al. [15]. They report that the effect of interference of two bodies is considerably large when G/b ratio is small and the re-attachment distance shortens while maximum values of transverse and vertical velocities are small due to interference of two identical bodies. In a recent study, interactions of tandem square cylinders at low Reynolds numbers were studied experimentally by Yen et al. [16] and the effect of Reynolds number, spacing ratio and rotation of angle of the downstream cylinder on the flow characteristic modes, drag coefficients and vortex shedding properties were investigated. They found that in the inertia-dominant flow field, the Strouhal number increases with Reynolds number while it decreases in the viscosity-dominant flow field.

The literature review given above shows that, and to the best of authors' knowledge, there is no work that has considered the flow field in the vicinity of tandem square cylinders under *shallow water* conditions. A shallow flow is one in which the horizontal dimensions are much larger than the vertical extent and the vertical component of water particle acceleration is negligible compared with the horizontal acceleration components so that the pressure variation can be assumed hydrostatic. Typical examples include wide rivers, lakes, coastal lagoons, estuaries, and so on. Hence, better understanding of the shallow flow hydrodynamics and related processes, such as flooding, sediment transport, spreading and mixing of pollutant and its effects on water quality, is of great importance. The flows around bridge piers as well as islands are examples of tandem arrangement in shallow flow.

Therefore, this study investigates the flow field in the vicinity of tandem square cylinders under *shallow water* conditions. Particle Image Velocimetry (PIV) measurement method is employed to study the flow patterns such as streamlines, vorticity and turbulence intensity structures near and between two circular cylinders placed in tandem.

2. Experimental set-up

Experiments were performed in a large scale closed-loop open-surface recirculating water channel, located in the Fluid Mechanics Laboratories of Çukurova University, facilitating the Particle Image Velocimetry (PIV) technique which yielded instantaneous and averaged velocity and vorticity fields. The water channel has dimensions of 8000 × 1000 × 750 mm and is made of a 15 mm thick transparent plexiglass sheet (Fig. 1). Water flow speeds were controlled by a 15 kW radial flow pump with a variable speed control unit. Before reaching the test chamber, the water was pumped into a settling chamber and passed through a honeycomb section and two-to-one channel contraction.

A schematic view of the test section mounted in the water channel system and used in the present experimental work is shown in Fig. 2. Measurements were taken both on side view and plan view. Location of laser sheet and camera is shown for both viewing planes in Fig. 2. Two identical square cylinders with $D = 28$ mm, manufactured from Plexiglas, were placed on a horizontal platform. The free stream velocity was kept constant at a value of 160 mm/s which corresponds to a Reynolds number value of $Re_D = U_\infty D/\nu = 4470$ where U_∞ represents the depth-averaged free-stream velocity. In all experiments, the water level was maintained at a depth of 14 mm. The distance between the cylinders, G, was changed in the range of 0–140 mm, which corresponds to a dimensionless gap ratio G/D of 0.5–5.

Horizontal (side view) and vertical (plan view) laser sheet orientations were employed to determine three-dimensional transverse structure of the flow. By this measurement technique, two-dimensional instantaneous velocity vector fields downstream of the cylinder were measured and flow properties were defined by quantitative images such as time-averaged vorticity contours, streamline patterns and Reynolds Shear Stress contours.

A laser sheet with a thickness of less than 1.5 mm was generated to illuminate the particles in the plane view. The flow was illuminated with two Nd:YAG pulsed lasers (532 nm) mounted with a single casing and operating nominally at 120 mJ/pulse. The