Experimental Investigation of Simple-Built and Low-Speed Water Tunnel as a Platform for Studying Fluid Flow Using PIV Measurements

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ABSTRACT

We present a thorough experimental investigation of a simple-built low-speed water tunnel that could facilitate the study of some of the primary fluid dynamic concepts based on quantitative flow measurements using Particle Image Velocimetry (PIV). The water tunnel system is designed and built using a simple arrangement of a double reservoir tank and a centrifugal pump that drives the fluid flow at low speed into a square cross-sectional and relatively short test section. The study shows that the system reasonably and steadily generates fully developed flows inside the test section with <20% of point velocity variations. Based on the fluid-structure tests, it is also observed that the system could produce moderately consistent boundary layer separation phenomena with the variance of the area mean vorticity within 25%. With this performance, we show that the system fulfills the essential requirement to be used as a simple, easy-to-operate, and easy-to-maintain educational platform to study fluid dynamic phenomena related to the interaction of a static sub-merged object and fluid flow.

Keywords: *Simple-Built Water Tunnel; Low Speed; Fluid Flow Measurements*

Introduction

The subject of fluid mechanics allows one to gain a quantitative and qualitative understanding and approximation for many practical applications. To achieve that, comprehensive, rigorous, and quantitative approaches are needed to study the physical phenomena properly. Many measurement techniques,

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apparatuses, and devices were developed to facilitate the in-depth study of fluid mechanics, such as flow visualization, static and dynamic pressure transducers, laser-doppler anemometer (LDA), etc. Flow visualization played an essential role in studying complex fluid flow problems such as multiphase flow behavior [1]-[2], which would be difficult to study via an analytical or numerical simulation alone. Furthermore, flow visualization is considered a non-invasive flow measurement technique that produces negligible disturbances in the flow. Particle image velocimetry (PIV) has been extensively used as an advanced and precise flow measurement technique based on tracer particle flow visualization [3]. PIV requires a medium to suspend the micron-sized particles to represent the local fluid kinematics [4].

Meanwhile, water tunnels have been known and used to study the physical phenomena (e.g., boundary layer flows) when an immersed object interacts with fluid flow inside an enclosed channel. While water tunnels could be applied for a static object, the practical use could also be extended to study fish swimming performance in a regulated environment [5]-[6]. Compared to its working fluid counterpart (i.e., air), water is considered more suitable as a medium with stable fluid properties for tracer particles in implementing PIV and flow measurement [7]. Therefore, a water tunnel could provide relatively precise and consistent experimental data to measure complex fluid flow characteristics [8]. The utilization of water tunnels and PIV has been demonstrated to be invaluable in various practical applications such as coastal study [9], turbulence study [10], micro air vehicle study [11], and fluid-structure interaction [12]-[13].

Despite its significant contributions to the study of fluid dynamics, water tunnel is still considered an expensive, bulky, complicated, and less developed studying platform for many educational institutions, mainly due to its size and therefore the requirement of immense space, enormous power consumption, and expensive built materials and equipment. Thus far, no specific technical literature thoroughly investigates the small and simple water tunnel system for educational purposes. This paper reports an experimental investigation of a simple build, small size, and low-speed water tunnel to quantitatively study some of the basic fluid dynamic phenomena. This work demonstrates the flow shear rate measurements on the boundary wall, flow velocity field measurement at different test sections, and flow separation using objects with distinct surface roughness, all based on PIV measurements. It is shown that the water tunnel produces reasonably close quantitative measurement data compatible with the theoretical prediction based on the systematic characterizations. As mentioned above, these outcomes are ideal for educational purposes to study the fundamental fluid dynamic problems.

Material and Method

This section presents the detail of engineering design, the water tunnel's experimental apparatus, and the flow measurement technique.

The water tunnel system and components

The water tunnel system incorporates two water tanks (310 × 310 × 500 mm) as the reservoir joined to the inlet and the outlet of the test section. The test section has a uniform square frontal cross-sectional area of 150 mm × 150 mm and a length of 3000 mm. Theoretically, this length is adequate to attain fully developed laminar flow at low-speed operation. The water tank and the test section were built entirely from Poly(methacrylate) (PMMA) with a 6 mm thickness. Figure 1 depicts the details of the water tunnel system.

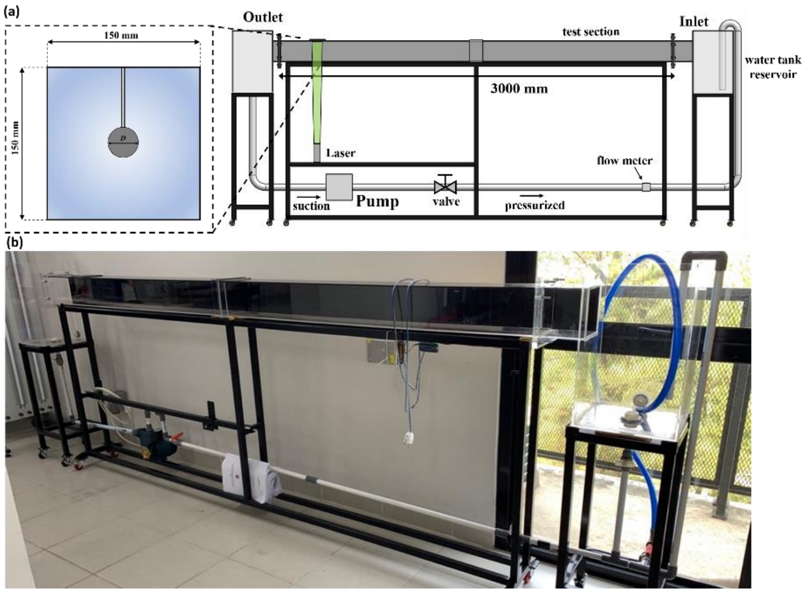

Figure 1: (a) The side view of the water tunnel system configuration and, (b) the embodiment of the water tunnel

The water tunnel system is designed for a continuous closed-loop water network propelled by an AC centrifugal pump (National GP 125, Indonesia). The fluid flow is driven by the pressure difference generated between the suction and the pressurized part of the pump, which has a maximum head, suction, and capacity of 27 m, 9 m, and 30 L/min, respectively. Meanwhile, to connect the pump to the water tank, we used a uniform polyvinyl chloride

(PVC) pipe and connector with an inner diameter $\phi = 0.5$ in. (≈ 12.7 mm). The water tunnel is also equipped with a main connecting valve at the pump's discharge side to control the flow speed by positioning the valve's lever. In our experiment, the flow speed is varied by adjusting the valve fully and half-opened. The valve was used for a simple and easy flow control mechanism, considering the centrifugal pump's rotational speed is fixed.

Here, we utilized spherical objects ($D = 50$ mm) with different surface roughness (i.e., smooth and dimpled) to study the flow separation phenomena. It is crucial to ensure that the surrounding object has enough space to minimize the boundary effect. In other words, it is essential to use an object with theoretically reasonable characteristic length compared with the boundary layer thickness developed on the test section wall such that the flow that surrounds the object is in the state of free streaming flow. The object dimension is comparable to the test section's cross-section area for a low-speed water tunnel. This arrangement is necessary to ensure plenty of room for the object exposed by the free streaming flow; hence, the boundary/wall effects become less significant.

In this build, the total cost of the water tunnel is below $ 1000 (detailed bill of materials is shown in Table 1), which is significantly low compared to the commercial one. In addition, due to the simple and relatively small build, the water tunnel is also easy to maintain and repair, making the setup suitable for study purposes.

Tabel 1: Estimated costs

No	Material	Volume	Cost (USD)
1	Acrylic sheets and processing	5 m^2	$ 500
2	Metal bars and processing	10 m	$200
3	Pipe, connector, valve	Sets	$70
4	Centrifugal pump	1 Unit	$40
5	Arduino, flow meter, electronic component	Sets	$60
6	Wheels, bolt, nuts, etc	Sets	$50

Flow measurements

Two flow measurement techniques were used to measure the average velocity in the fluid network and characterize the velocity field inside the test section. The average velocity of water flowing at the pump's discharge side is measured using a water flow sensor (Sea YF-S201) with a resolution of 0.1 L/min. The sensor is connected to an Arduino processor to record the volumetric flow rate data as a reference for the flow velocity at the test section entrance.

Meanwhile, in the test section, we use the particle image velocimetry (PIV) setup (H-41, Armfield) using 100 μm polyamide tracer particles to visualize the velocity field, the velocity profile, and measure the average velocity. A synchronized CMOS camera and laser diode pulse (λ = 660 nm) system were arranged with a pulse separation of 40 ms and a pulse width of 15 ms during the image acquisition process. Moreover, for further PIV post-processing, we also use PIVLab [14] to visualize the velocity magnitude, the shear stress, and the vorticity data analysis. The particle image velocimetry setup is shown in Figure 2.

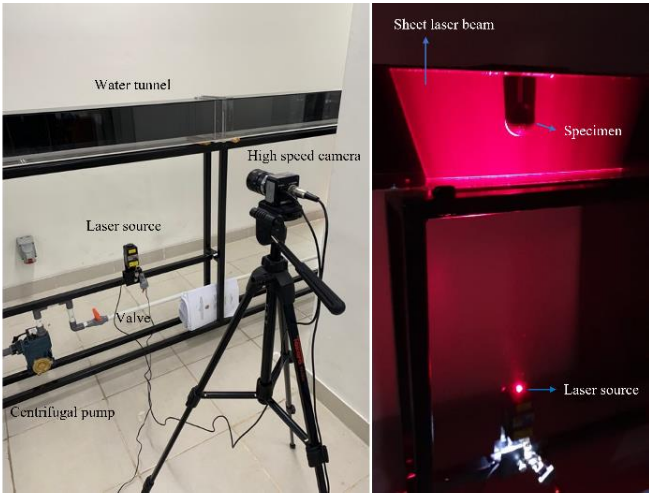

Figure 2: Particle image velocimetry setup

Result and Discussion

Flow characterizations

We characterize the flow inside the water tunnel system by measuring the flow rate of two different valve openings (i.e., full and half-opened) obtained from the flow sensor on the pump's discharge side. The average flow rate was measured during steady pump operation and recorded for 120 seconds, with a sampling time of one second. Figure 3 compares the flow characteristics in terms of the valve opening. From the results, it is shown that the flow rate fluctuates during operation. This flow characteristic is expected and widely known due to pressure pulsations in centrifugal pumps [15]–[17]. Therefore, it is essential to get the mean value of the flow rate. Based on experimental results, the average flow rates of fully-opened and half-opened valve configurations were 18.5 L/min and 21.3 L/min, respectively. Furthermore, the fully-opened valve configuration has a slightly lower flow rate variation relative to its average flow rate value (i.e., 0.23%) than the half-opened one (i.e., 0.32%). This slight discrepancy hardly affects the flow characteristics in the test section.

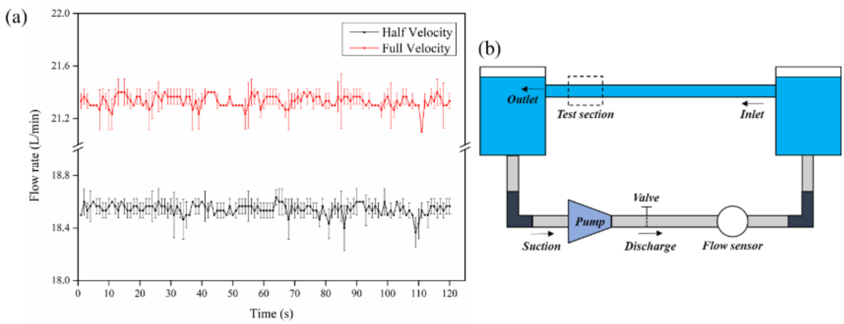

Figure 3: (a) The flow rate characteristics of half-opened and fully-opened valve configuration and, (b) the schematic of the water tunnel's flow configuration

To ensure fully developed flow, we measure the velocity profile at different positions situated ~600 mm (designated as 'left') downstream and ~900 mm (designated as 'right') upstream next to the test object position. The experiment was conducted in the fully-opened valve configuration using particle image velocimetry (PIV). The velocity profiles of the flow at the left and the right positions are shown in Figure 4. It is shown that the velocity profiles were both asymmetric, in which the lower half of the flow moves slower than the upper half. Despite this, the right side's velocity profile and the left side showed a similar pattern, indicating fully developed flow. Also, the time-averaged velocity flow has decreased ~6.6% from the right side to the left side at the test section's mid-depth due to the friction loss. This flow characteristic is sufficiently ideal to be used in the test section area that is located 600 mm from the left side.

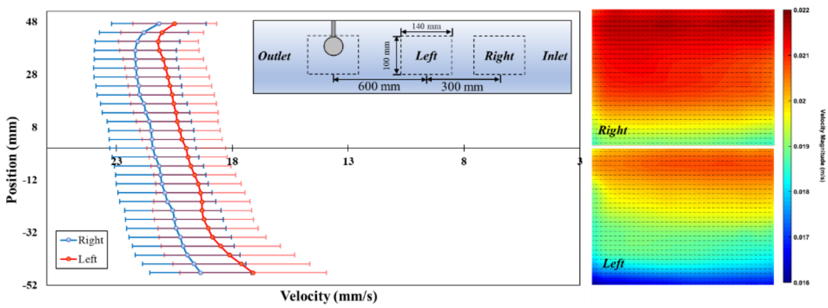

Figure 4: Velocity profile at two different positions (i.e., left/downstream and right/upstream) with fully-opened valve

We also characterized the flow velocity profile inside the water tunnel using the half-opened and fully-opened configurations. The time-averaged velocity profile in both settings produces a slight variation in the flow pattern (Figure 5). Based on different valve openings, the average velocity has been successfully reduced by ~16%; this feature could be useful for users to have a bit of range of the flow velocity inside the test section. This flow velocity variation provides more measurement options to observe and analyze the hydrodynamic consequence, especially in flow-sensitive phenomena (i.e., fluid-structure interaction). While it is practically possible to further reduce the flow velocity by throttling the valve, reducing valve opening lower than half-opened is not recommended due to a potential threat of damage to the centrifugal pump with continuous operation for an extended period.

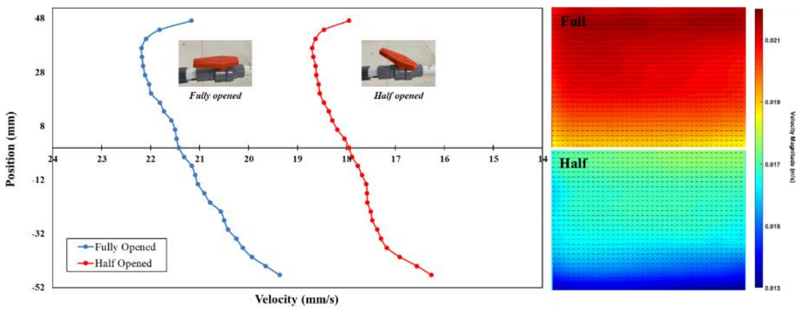

Figure 5: The velocity profile of the fully-opened and half-opened valve

Flow shear rate inside the test section

According to the PIV analysis, the velocity profile inside the test section is slightly asymmetric/skewed. This phenomenon could happen due to a somewhat different shear rate between the fluid and the surface perpendicular to the flow direction. Here, we perform the shear rate analysis at the top and bottom fluid-wall boundary to investigate the resulting velocity profiles. Figure 6 shows the shear rate plots at the bottom and the top boundary with two different valve openings (i.e., full and half-opened).

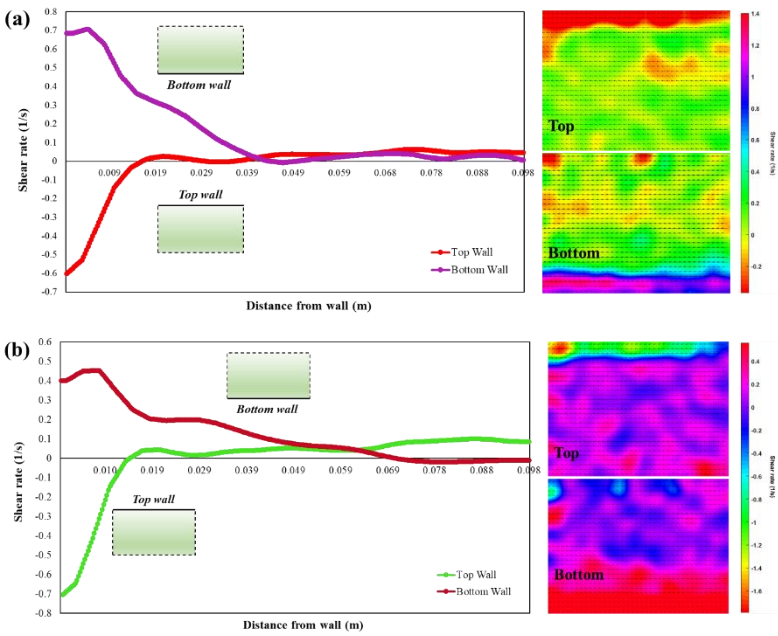

Figure 6: The flow shear rate at the top and the bottom of the water tunnel's wall with (a) fully-opened and, (b) half-opened valve configuration performed by PIV

The shear rate profiles were extracted, averaged, and plotted along a vertical line at the very edge of the field of view. It is clearly shown that the bottom wall consistently has a more considerable shear rate value than the top wall. The shear rate has a different characteristic when compared between the fully-opened and half-opened valves. Despite their similar maximum shear rate value, the shear stress layer at the fully-opened valve seemed thicker at the bottom wall than at the top wall. Meanwhile, the shear stress layer was slightly thinner at the half-opened valve. The maximum shear rate value was also reduced by approximately 36% compared to the fully-opened valve. However, the shear stress persisted, developing at the bottom wall, creating the asymmetric velocity profile across the test section. We argue that this distinction was predominantly due to the difference in the hydrostatic pressure between the lower half and the upper half of the test section area. This idea is entirely possible because, in our design, the test section channel was not vertically positioned and attached to the middle part of the water tank. The asymmetric flow could be fixed by applying a flow conditioner to ensure the flow that enters the test section becomes uniform [18] with additional building costs.

Furthermore, it is important to note that PIV is a light-sensitive flow measurement method prone to generating inaccuracies and variances in quantitative measurements. The sources of errors could be lighting distortion such as ambient/background lighting or reflections of light from the test objects on the wall boundaries. In our analysis, the measurement errors were also attributed to these factors.

A case study of vorticity

This section presents a simple fluid-structure interaction case study to briefly demonstrate and investigate the flow separation phenomena as the effect of the surface roughness by measuring and calculating the area mean vorticity at the wake region. Here, we used two sphere objects that were located in the area center of the test section, each with a smooth and dimple surface. In a laminar flow, the drag coefficient is inversely proportional to the Reynolds number (Re). Therefore, we reconstructed the idea by varying the flow velocity using the fully-opened and the half-opened valve configuration.

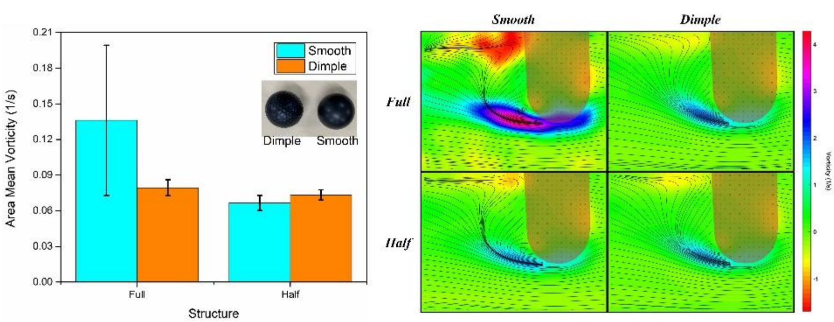

Figure 7: The comparison of the area mean vorticity of smooth and dimple objects with different valve opening

Figure 7 shows the area mean vorticity (ζ) extracted from PIV results based on Equation (1) [19].

$$\zeta = \frac{\sum_{i=1}^{n}\left(\frac{\partial \vec{v}}{\partial x} - \frac{\partial \vec{u}}{\partial y}\right)_i}{n} \tag{1}$$

where $\vec{u}$ is the *x* component of the *i-th* velocity vector, $\vec{v}$ is the y component of the *i-th* velocity vector, and n is the number of vector field cells.

We show that the dimple structure has a lower area mean vorticity than the smooth one, meaning that the dimple structure produces less vortex. In addition, the dimple structure has a smaller area mean vorticity variation. This phenomenon is theoretically acceptable since the increased surface roughness would reduce the coefficient of drag (C_D) by extending the flow separation point. At lower velocity, however, the effect of the dimple surface was not visible due to the characteristic of the coefficient of drag at a lower Reynolds number (Re $\lesssim$ 400). From the perspective of vortex's variance, the smooth surface produces considerable vorticity variation due to chaotic wake flow, especially in the case of a fully-opened valve (i.e., maximum flow speed). This phenomenon would generate a significant variation (indicated by the error bars) in the vorticity measurement. The variance of vorticity in the fully-opened valve for the smooth surface was 0.063 $s^{-1,}$ while the variance of vorticity on the dimple surface was 0.0067 s^{-1}. However, as the flow speed was reduced in the half-opened valve, the vorticity variance for both smooth and dimple was almost similar, i.e., 0.0063 and 0.0043, respectively.

Conclusions

In conclusion, we have investigated a simple-built, small-size, and low-speed water tunnel system that could be used in a higher educational setting to study fundamental topics such as flow measurement and fluid-structure interaction. Based on the testing performances, the water tunnel could generate almost entirely fully developed velocity profiles at the test section with medium point velocity variance (less than 20%). Furthermore, it is also shown from the fluid-structure interaction tests that the boundary layer separation phenomena were observed reasonably consistent with moderate area mean vorticity variance, i.e., within 25%. Despite its limitation, in our opinion, the system can still be useful and implemented, particularly for educational purposes and potentially for research purposes.

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