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Research Article

A Laboratory Study on the Design and Performance Evaluation of Pitot-Tube

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Abstract

Due to the increasing demand for water resources worldwide, this commodity and its spatial and temporal properties are of the interest for decision makers and scientists. On the other hand, the accuracy in detecting the physical characteristics of the water flow such as velocity is among the most important aspects of the hydraulic studies. The pitot tube, which is not widely used in the open channel hydraulic practices, is one of the equipment used for determination of the flow velocity. In this study, we have addressed the design, fabrication, and laboratory experiments related to a pitot tube to investigate its applicability for open channel experiments. A 3D-printed pitot-tube is designed and used in a set of experiments carried out in an open channel, with different flow rates (three experiments). As a result, the relative error rates were interpreted by comparing the velocity rates obtained with the help of the water level difference in the differential manometer (V_m) and the velocity rates obtained from the flow continuity equation in the open channel (V_o). Results indicated a 50% bias, while the scatter analysis showed that the associated deviations match a linear equation and once used in the interpretation of the results, the linear transformation reveals a 3% bias in the experiments.

Keywords: 3D-printer, Flow velocity, Open channel hydraulics, Pitot- tube design

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1. Introduction

The sustainability of water and water resources in general is important in evaluation and exploitation of the roadmaps of the modern societies. Due to the increasing demand for the fresh water resources, conducting studies for determination of the flow characteristics such as the velocity, flow rate, surface water profiles, and the water depth seems inevitable. As a result, the continuous investigation of such parameters has an important role both in examining the behavior of the flow and in the design and planning of the hydraulic structures. The velocity of flow, is one of the most important characteristics of the flow, and a key parameter in determining the erosion, sediment movement, the permanency of the flow, the flow conditions (subcritical or supercritical), and the amount of flow passing through a section. So far, the previous laboratory and field studies on the transmission capacity and velocity of the water in open channels have revealed valuable information about the basic principles of the phenomena [1-7]. Along with the most well-known theoretical methods such as continuity, Manning's, and Bernoulli's equations; alternative methods/equipment such as current meter (e.g. hydrometric reel), orifice-meter, Particle Image Velocimetry (PIV) or laser aided measurements, and Acoustic Doppler Velocity Meter (ADV) are used in previous studies [8]. For instant, current meter (sometimes called as Muline) has a propeller that rotates with the movement of water. The flow rate is usually calculated afterward, by taking into account the number of revolutions during the rotation of the propeller [9]. On the other hand, Orifices are simple instruments used to measure the flow rate under constant load in water tanks or pipes. Hence, the flow velocity can be obtained theoretically with the help of Bernoulli equation. Alternatively, the ADV is a device that measures and records the water flow velocity via emitted sound waves at different depths, that hits the particles in the water, and returns to the ADV for the evaluation [10]. Pitot-tube is also an alternative equipment for measuring the velocity in a fluid (gas or liquids), while its application is mostly limited to the gases. This device with intertwined pipe system, takes the difference between the dynamic and hydrostatic head. Afterward, with the help of Bernoulli's equation, velocity of the flow can be acquired. In this context, previous studies showed that in practice the application of Pitot-tube in measurement of velocity provides consistent results [11-15]. In a study conducted by Ghaznawi [16], an open channel of 0.055 (width) × 1.44 (length) m was used. In the conducted experiments, velocity rates were measured using a fabricated Pitot-tube, with a ruler and a medical infusion set. The velocity and pressure distributions were calculated both numerically and experimentally, and compared with the water depths and velocity rates obtained by the experiments. Afterward, the velocity profiles were examined and the differences were determined between the experimental and numerical results in the regions close to the water surface at the upstream. When the Normalized Root Mean Square Error (NRMSE) results calculated for the velocity profiles in all experiments were examined, it was concluded that the differences decreased with the increase of the flow rate. When the velocity measurements taken on the applied weir were examined, it was concluded that the experimental and numerical results were more consistent at the upstream region. As a result, an agreement between the experimental and numerical results was obtained and therefore, the application of the fabricated Pitot tube was suggested for further application. In the study conducted by Demirel [17], the most suitable model was investigated for the determination of hydropower potential in small river basins, while the velocity measurements were carried out using floats and a Pitot-tube method. In the performed field measurements of small rivers without the gauging stations, the cross-sections considered in the float method were also measured with the help of Pitot-tube. Afterward, the velocity rates obtained by floats and Pitot-tube methods were evaluated, and the instantaneous flow rates were estimated in three-month periods representing the precipitation regimes of eight streams that do not have a gauging station. It was concluded that the difference between the flow rates measured with the Pitot-tube and the float method was quite small and negligible.

According to the brief statement of the art detailed above, and due to the continues need for confirmation or confrontation of the idea, this study aimed to address the application of the Pitot-tube once again for open channel flow practices. To achieve this, a Pitot-tube is designed and fabricated to be used in a set of laboratory experiments. Initially, the Pitot-tube is designed and fabricated using a 3D printer (i.e. stereolithography based). Then, a differential manometer is used in order to read the dynamic and hydrostatic heads of the flow measured by the Pitot-tube. Alternatively, the flow velocity determined using the flow depth before the forefront of the Pitot-tube, later to be used in continuity equation. Finally, the velocity rates obtained by continuity equation and the fabricated Pitot-tube are compared with each other to confirm the degree of concordance between the data sets. Hence, the following sections addresses the theoretical aspect and background of Pitot-tube and differential Manometer equipment later to be followed by the 3D design, fabrication, lab experiments and result section.

1.1. Pitot Tube

Pitot-tube is made up of two nested pipes, that is used in measuring the velocity of fluids. While the outer pipe measures the static pressure (in here hydrostatic head), the interior pipe is for measuring the dynamic pressure caused by the movement of the fluid [18]. The outlets of these pipes, are then connected to a differential manometer, that measures the height, h to determine the point velocity of the flow with the help of well-known $V=\sqrt{2gh}$ equation. Pitot tubes can be designed and fabricated with consideration to the basic principles given in the statement of the art. According to Berkun [19], the diameter of the outer pipe in the Pitot-tube should be considered twice the diameter of the inner pipe, and seven holes must be provided to measure the static pressure (Fig. 1). The other must, is the distance of the provided holes to the forefront of the Pitot-tube, that is six times the diameter of the outer pipe (6D), while the distance from the Pitot tube anchor (forefront) to the center of the perpendicular tip (elbow) should be 14 times of the outer pipe diameter (14D).

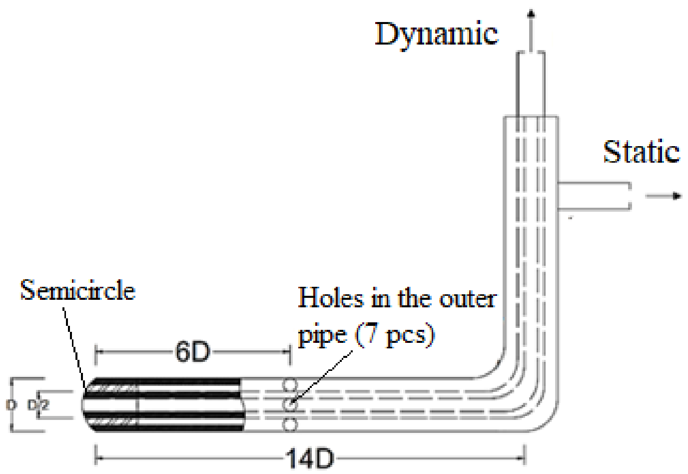

Figure 1. Pitot-tube impact tip and design principles [19]

1.2. Differential Manometer

A differential manometer is usually used to measure the pressure differences between two desired points with the help of a U-shaped pipe filled up with a liquid of a known specific gravity. In this respect, it can be used to measure the pressure gradient between the dynamic and the hydrostatic heads of a flow at a specific location [20]. Therefore, in practice a differential manometer is generally preferred in measurement of a specific fluid (Fig. 2) that provides eligible reads.

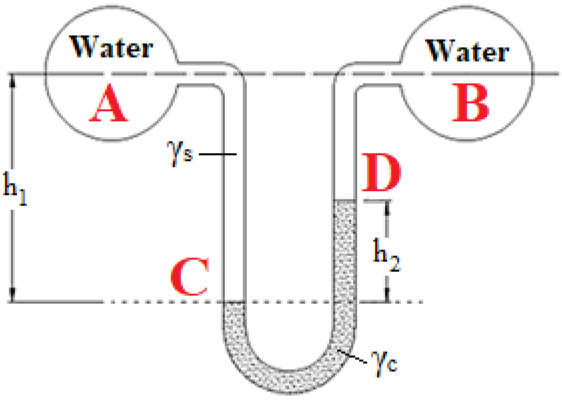

Figure 2. Differential manometer

Consequently, in the present study a differential manometer is connected to the fabricated Pitot-tube to measure the head gradient between the pipes. The pressure difference between the pipes can be calculated as,

$$P_A + h_1\gamma_s = h_2\gamma_c + (h_1 - h_2)\gamma_s + P_B \quad (1)$$

Therefore, the pressure difference (ΔP) between point A and B can be determined as,

$$\Delta P = P_A - P_B = h_2(\gamma_c - \gamma_s) \quad (2)$$

In these equations, γ_c, γ_s, h_1, h_2, P_A and P_B are the specific weight of the liquid in the manometer (dyed water is used in this study), the specific weight of the fluid (water in the channel), the manometer head in point A, the manometer head in point B, the manometer pressure in point A, and the pressure of manometer in point B respectively. Afterward, the difference between point A and B could be calculated using h_2 and the difference between the specific weights of the liquid in the manometer and the containers [19].

2. Materials and Methods

The design, fabrication, and experiments of this study are all carried out in the Hydraulics Laboratory of Civil Engineering Department at Bursa Technical University located in Bursa province of Turkey. In this respect, the following sections addresses, the design and fabrication of the Pitot-tube and the conducted open channel experiments at the laboratory.

2.1. Pitot tube design

In the first stage, an 8 mm diameter (D) is selected for the fabrication of the Pitot-tube by examining the commercially available samples. Based on this reference value, the inner diameter of the pitot-tube is determined as 4 mm (D/2); while the distance of the holes from the forefront of the tube is determined as 48 mm (6D). Additionally, and along with these criteria, the length of the tip parallel to the current is considered to be 112 mm

(14D). The outlet of the pipes is then fabricated at the same length, parallel to the direction of the upstream flow (Fig. 3a).

The Fusion 360 software is then used for the 3D sketching and designing of the Pitot-tube with respect to the dimensions detailed before (Fig. 3b). The designed Pitot-tube is then sliced with 0.05 mm resolution (i.e. defining thickness and number of layers for 3D printing) and made ready for 3D printing with the help of Anycubic Photon Workshop 64 software, commercially available for purchasing the Anycubic Photon M3 Max 3D printer (available at the laboratory). As a printer that uses stereolithography (SLA) rather than Fused Deposition Modeling (FDM), a UV-sensitive liquid Resin with 1.05 ~1.25 g/cm3 density and 150 for m Pa·s viscosity is used in fabrication of the pitot-tube. Once exposed to the UV lights of the SAL machine, it solidifies and fabricates the solid object as expected. Hence, relatively adequate number of supports are used in bottom and sides of the Pitot-tube for protection of the 3D printed object (i.e. pitot-tube) and avoid fabrication errors (Fig. 3c). The 3D printing fabrication with ± 0.05 mm precision, is then initiated and successfully lasted after 1.5 hrs (6 cm/hr in average). Afterward, in order to clean the excess liquid resin and enhance the 3D printing quality, the fabricated Pitot-tube is washed using Isopropyl Alcohol (C3H8O) and normal tap water (H2O); and then cured with the UV rays with the help of Anycubic Wash and Cure Plus machine. Finally, an air compressor is used to remove the excess liquid remains inside of the Pitot-tube, and the final installation and assembly between Pitot-tube and differential manometer is achieved.

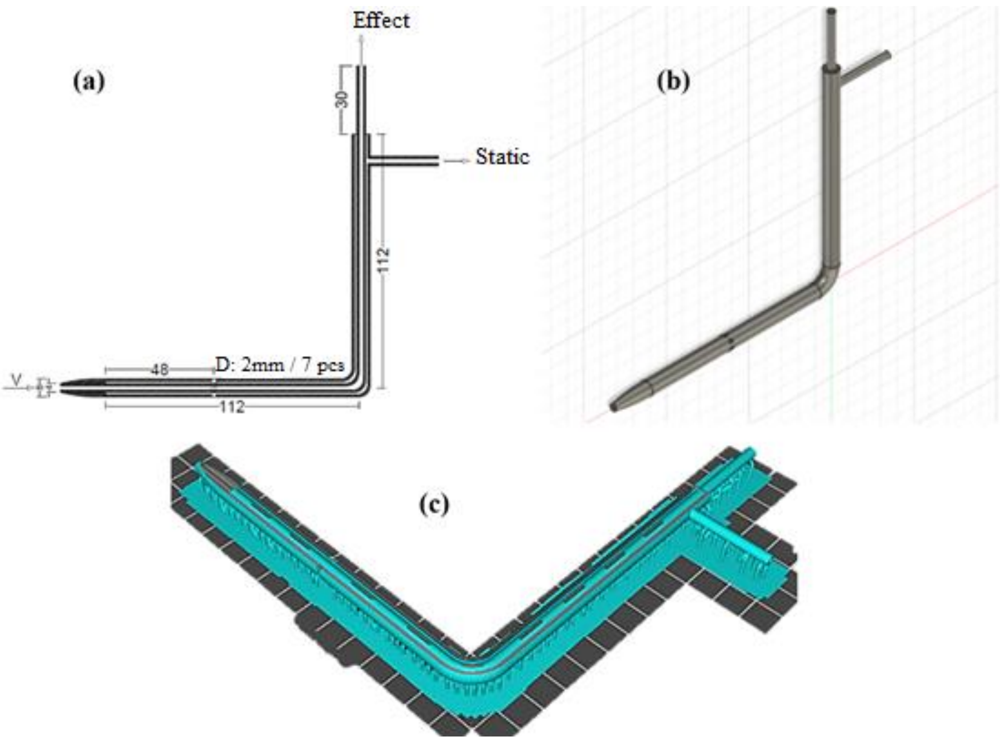

Figure 3. Pitot-tube (a) designed dimensions, (b) Fusion 360 design, and (c) prepared object in Anycubic Photon Workshop 64

2.2. Open Channel Experiments

As detailed before, initially the Pitot-tube and differential manometer are connected with each other (Fig. 4a). The water head reads of the differential manometer were made readable by dying the water with red food coloring. An open channel with 200×10× 9 cm dimensions is then used in the experiments, while a cross-section located at the 120 cm (A relatively distance from the upstream gate and the honeycomb (to regulate the flow) that assumed to be long enough to reach a stationary state) form the upstream is used for conducting measurements (Fig. 5). In the experiments three different volumetric discharge as 11.02, 9.80, and 8.57 m3/hr based on the capacity of the circulation pump (Max-Min) are also used to conduct the experiment.

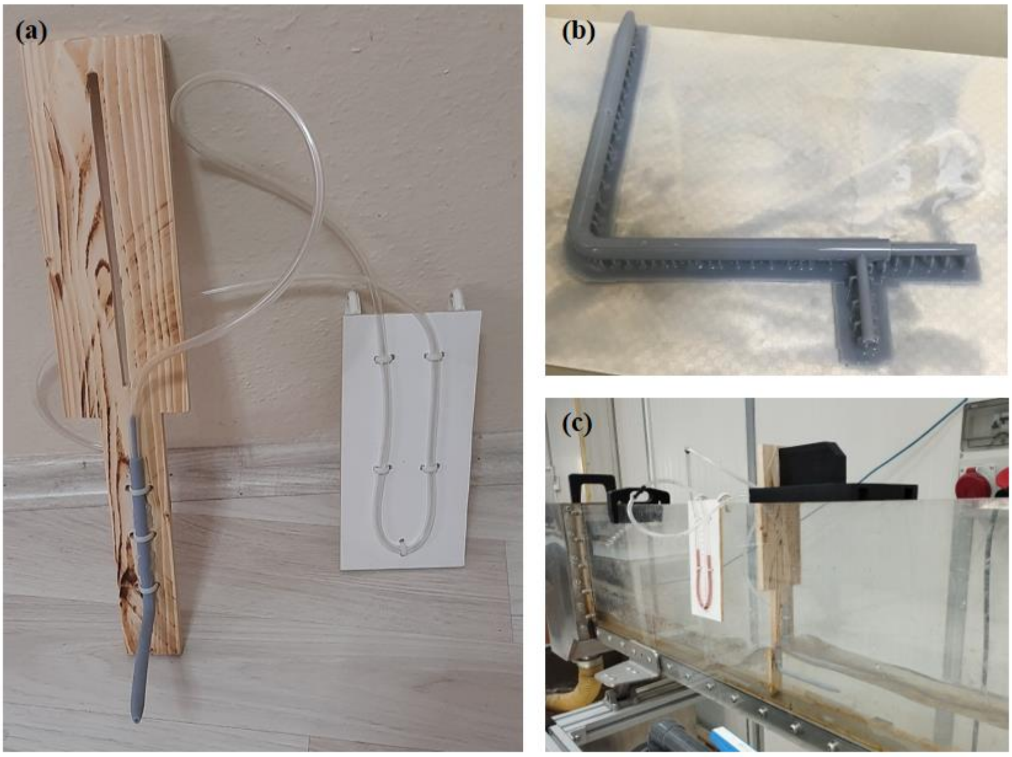

Figure 4. The ready to use (a) Pitot tube and the attached manometer, (b) the 3D printed Pitot tube, and (c) the conducted experiments in the open channel

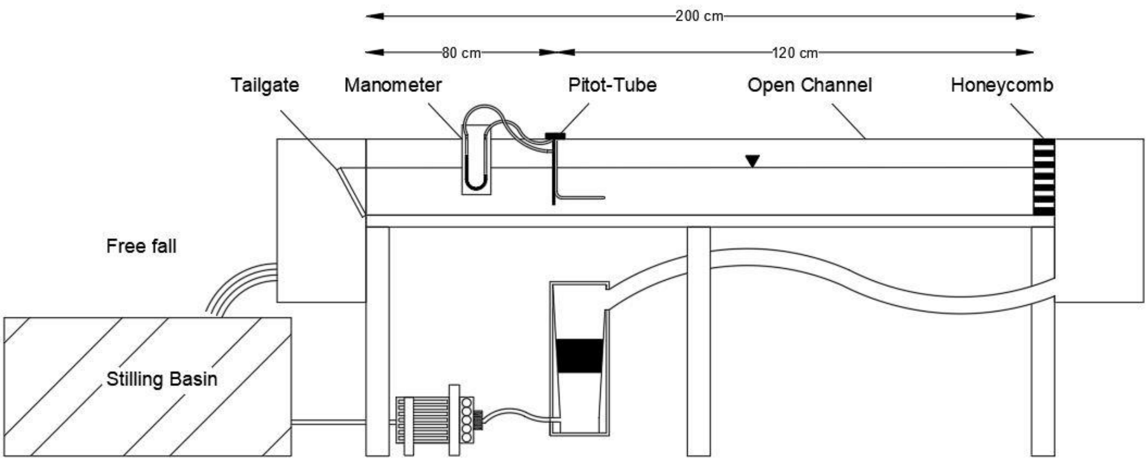

Figure 5. Open channel and location of the Pitot-tube

In the experiments, the pressure difference between points B and C in Fig. 6 is equal to the height *(h)* read on the manometer. Afterward, the Bernoulli's equation is applied by ignoring the height difference between two pipes as,

$$\frac{P_B}{\gamma} + 0 = \frac{P_C}{\gamma} + \frac{V^2}{2g} \quad (3)$$

Hence, the velocity (*V*) could be determined using,

$$V^2 = 2g\left(\frac{P_B - P_C}{\gamma}\right) = 2g\left(\frac{\Delta P}{\gamma}\right) \tag{4}$$

or

$$V = \sqrt{2gh} \tag{5}$$

while, P_B and P_C denotes the amount of pressure generated in the Pitot-tube tip and the holes, respectively. In addition, V represents the intended flow velocity, while γ, g, and h represent the specific weight of the water, the gravitational acceleration and head dıfference reads from the manometer, respectively. For this, h, the water level difference between the two pipes, is substituted in Eq. 5 to obtain the measured velocity of the flow (Vm).

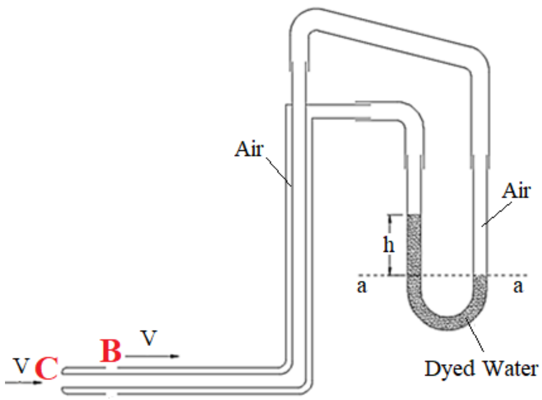

Figure 6. Combined Tube Manometer

Alternatively, the observed velocity (V_o) is determined using continuity equation as,

$$V_o = \frac{Q}{b \times h_c} \tag{6}$$

where Q is the flow rate read (i.e. 11.02, 9.80, and 8.57 m^3/hr) by the flowmeter in the open channel; h_c is the water level in the channel and b is the channel width. The obtained V_o data is then used to evaluate the accuracy of the V_m values obtained by the Pitot-tube during the experiments. Therefore, the error (ε) is calculated as,

$$\varepsilon = \left|\frac{V_o - V_m}{V_o}\right| \times 100 \tag{7}$$

that could be used in evaluating the performance of the design.

3. Results

After which the Pitot-tube is fabricated, experiments are conducted in the open channel flow (at the 120 cm from the upstream) using 11.02, 9.80, and 8.57 m^3/hr flow rates. In this stage, by considering the head difference (h_{dif}) between dynamic (h_D) and static (h_s) head in the pitot-tube the velocity of the current in the channel (Eq. 5) is obtained (V_m). Alternatively, the velocity of the current at the same point was calculated (V_o) with the help of flow depth, discharge and Eq. 6. Table 1, provides the obtained values for the aforementioned values, whilst the data are then used to determine the bias between V_0 and V_m reads approximately as ε (1): %52. This determines that the relationship between V_o and flow rates is stronger than the V_m calculated with the Pitot-tube. Fig. 7a depicts the relationship of discharge rate (m^3/hr) with V_o and V_m. The provided scatter diagram showed that the relationship is quite linear with high determination coefficient. But, the V_o rates are the twice of V_m rate (Fig. 7b). However, the

V_m reads could simply be transformed linearly to V_o with a help of a linear equation given in Fig. 7c. Hence, with a 92% concordance the provided linear equation can be introduced for further applications.

Table 1: Data evaluation chart (Q: discharge; h_D: dynamic head; h_s: static head; h_{dif}: head difference between h_D and h_s; V_0: velocity of current (Eq.6); V_m: velocity of current (Eq.5); ε (1): the bias between V_0 and V_m; V_T: transferred velocity with the help of Equation in Fig 7c.; ε (2): the bias between V_0 and V_T)

Exp. No.	Q (m³/hr)	h_D (cm)	h_s (cm)	h_{dif} (m)	V_o (m/s)	V_m (m/s)	ε (1) (%)	V_T (m/s)	ε (2) (%)
1	11.02	8.01	8.80	0.008	0.85	0.40	53.42	0.83	2.35
2	9.80	8.05	8.81	0.008	0.76	0.38	49.26	0.79	3.94
3	8.57	8.20	8.71	0.005	0.66	0.31	52.65	0.64	3.03
Mean	14.69	8.08	8.77	0.007	0.75	0.36	51.77	0.75	3.11

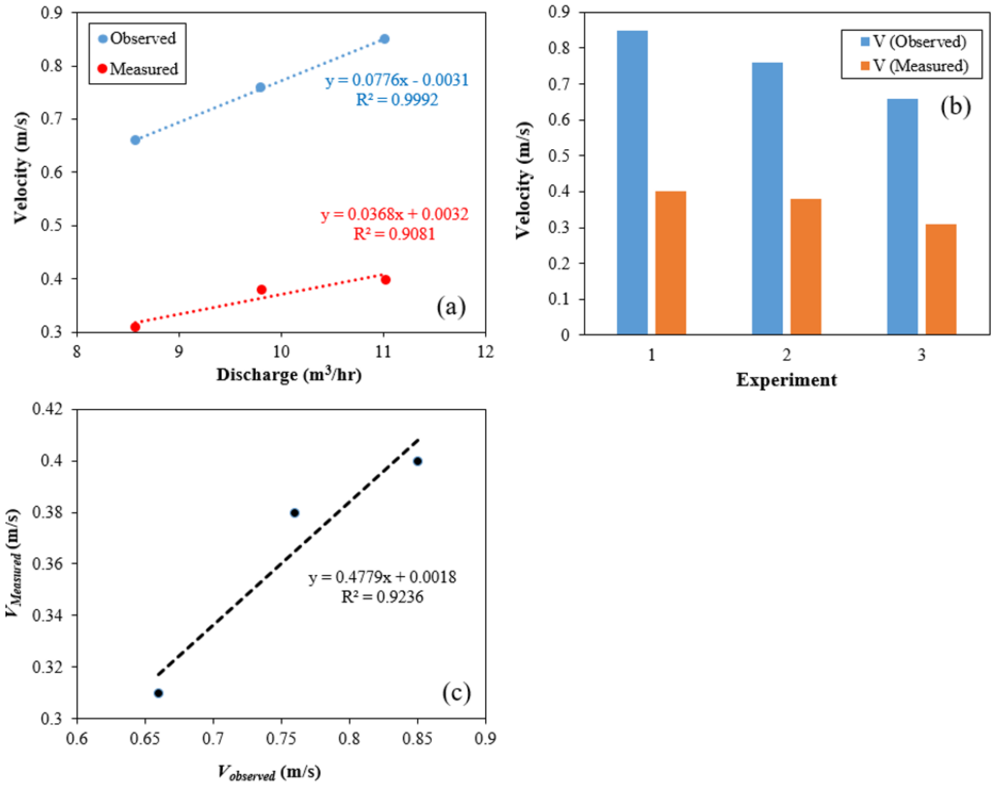

Figure 7. Results given as (a) a scatter plot of discharges vs. velocities and (b) bar chart of the V_o and V_m, and (c) the scatter plot of the observed vs. measured velocities

Therefore, the provided equation in Fig. 7c can be arranged as

$$V_T = \frac{V_m - 0.0018}{0.4779} \quad (8)$$

to obtain the transformed velocity reads (V_T) and use them instead of Vm in the comparison against Vo.

As also provided in Table 1, the mean values of the VT and Vo matches perfectly, and the rate of bias sufficiently drops to ε (2): %3.11. Therefore, the fabricated equipment could be used with a help of an adjusting equation (i.e. Eq. 8). However, as the reads in the channel were conducted with the flowmeter and the classical volume-time method, the illustrated performance of the tube could be caused by the dimensions of the Pitot-tube which was preferred based on the sensitive commercial samples that are usually used in the measurement of the velocity of gases rather than liquids. When liquid is used, sometimes the capillary force in the tiny run between nested pipes cause blockage and avoids current flow. The geometry of the Pitot tube that can cause precision in the experiments however, was preferred with a pointy end which may cause in aerodynamic behavior, yet other samples with flat forefront may present more accurate results. It is also known that the velocity distribution of the fluid through the cross section varies relative to the friction force originated from the interaction of the fluid with the solid surfaces (i.e. bottom and sidewalls) or the presence of turbulence volatilities. Our results, in concordance with the previous studies [21, 22], showed that the application of Pitot-tube in the open channel experiments is effective but also tricky. Yet, based on the preliminary studies conducted by Henry Darcy in 1856 and the latter review by the Brown [24] detailed experiments should be carried out to come across accurate reads. The limitation of this study, mainly is based on using alternative geometries in fabrication of the Pitot-tube, conducting relatively large number of experiments, and also using different scenarios (e.g. different discharge rates, bed slopes, cross sections, and depths).

4. Conclusion

In this study, the design principles of a Pitot-tube are addressed to obtain the velocity of water in an open channel of the laboratory-scaled studies. First, a Pitot tube is designed based on the principals provided in the statement of the art and then fabricated with the help of a 3D printer and liquid resin. In the next step, the fabricated Pitot-tube is connected to a Differential Manometer and used in the experiments. Observation rates are obtained by using the continuity equation, while the experimental velocity is determined with the help of the Manometer. Afterward, the observed and measured velocities are compared to determine the accuracy of the Pitot-tube reads. According to the initial results, the velocity of the Pitot tube has a relative 52% error compared to the classical reads. It has been concluded that different geometries and sensitivity analyses could possibly enhance further design attempts. But, with a help of linear equation, data reads are transferred and the relative error of 3% is achieved that could be considered as satisfactory.

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Nomenclature

The following abbreviations and symbols are used in the manuscript, while the symbols with different indices are detailed in the text.

Abbreviations		**Symbols**	
3D	3 Dimensional	γ	Specific weight [M L^{-2} T^{-2}]
ADV	Acoustic Doppler Velocity Meter	ε	Error (bias or precision)
FDM	Fused Deposition Modeling	b	Width of the channel [L]
PIV	Particle Image Velocimetry	g	Gravitational acceleration (9.81 $m.s^{-2}$) [LT^{-2}]
NRMSE	Normalized Root Mean Square Error	h	Height difference in differential Manometer [L]
SLA	Stereolithography	D	Outer diameter of the Pitot-tube [L]
UV	Ultra Violet	P	Pressure [M L^{-1} T^{-2}]
		Q	Discharge rate [L^3T^{-1}]
		R^2	Determination coefficient
		V	Velocity [LT^{-1}]

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