In-house PIV laser system design and development for measuring the velocity of liquids

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ABSTRACT

Measuring the velocity of fluids is important for different scientific applications in industry. There are different methods for measuring the velocity of fluids such as the Pitot tube, orifice plate, Venturi tube and via a rotameter. As these methods are clearly invasive they present considerable errors. Consequently, an optical method could be used for measuring fluids with substantial error reduction. Among those, Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV), Laser Doppler Velocimetry (DLV) are good options. In this work, a low-cost, in-house PIV laser system for measuring the velocity of a liquid in experimental form is developed based on our design. The results were then compared with the results of a rotameter at 2-5 litres per minute (LPM) in similar flow conditions. Full design and development of our system will be included in the manuscript.

Key words: PIV, laser sensor, velocity of fluids, uncertainty.

1. Introduction

Liquids and gases are used in Industry in a great number of applications such as hydraulic systems, textile industries and generate hydraulic.

Different kinds of devices are used for measuring the velocity of a fluid, such as, Pitot tube, Orifice plate, Venturi tube and rotameter; but, these devices generate measurement errors because these devices are on direct contact to the fluid and its measurement of velocity interferes with the results.

Some techniques work with optical components and these are used for reducing the measurement errors. For instance Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) and Laser Doppler Velocimetry (LDV) [1].

The laser sensor described in this work is based on the PIV technique for measuring the velocity of a fluid (water). A commercial laser at 445 nm with a power up to 5 W and a mini spectrometer Ocean Optics USB 4000 for detecting the propagation time of a particle through to fluid with a constant longitude, were the components integrated in the optical sensor.

Also, an artificial hydraulic system was made for measuring the velocity of a fluid, the area of the hydraulic channel is constant, and the flux is turbulent. All measurements of this research were realized in a controlled environment in the fluids laboratory at CIITEC-IPN in Mexico.

2. Design of optical sensor and hydraulic system

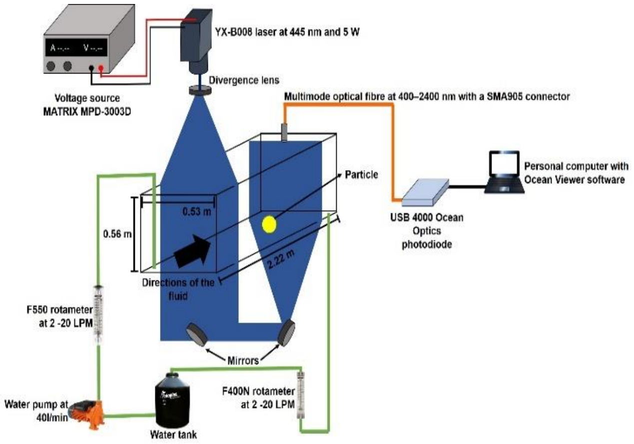

Figure 1. Design of optical sensor and hydraulic system.

The hydraulic and optical systems integrate the design of experimental sensor for measuring the velocity of a fluid.

A container (2.22 m x 0.53 m x 0.56 m), two rotameters (F550 and F-400N), a water tank and water pump (40 L/min) conform the hydraulic system. The water is propagated through the hydraulic system and its devices are connected from a PVC tube (1/2 in).

A pump source (MATRIX MPS-3003D), a laser at 445 nm (YX-B008), a plano-convex lens, two mirrors, an USB4000 Ocean Optics spectroscopy and a laptop integrate the optical system. These devices are installed on hydraulic system shown in the Figure 1.

2.1 Optical sensor operation

The optical sensor described here operates as the so-called PIV method, it uses the following velocity equation [1]:

$$U(x,t) = \frac{\Delta x(x,t)}{\Delta t} \qquad (1)$$

Where, "Δx" is the propagation of a particle on a longitude "x" on the time "t" over a short range on the time "Δt".

The water is propagated trough the hydraulic system, and the laser is operated, its beam is propagated and refracted trough the fluid to be measured, then, the laser beam is reflected on two mirrors generating two laser references with a "x" longitude trough the fluid, finally, the laser beam is detected from the spectrometer that is connected to a laptop.

A leaf is used as the particle used for measuring the velocity of fluid; the particle is added into the container following the propagation of the flux through the hydraulic system that simulates a river while the water is propagating on that. The leaf passes through to the beam references and break the communication between the beam laser and the spectroscopy. The longitude between the laser beam references and the time of propagation of the particle trough the laser beam references is known, with these data it is possible to calculate the velocity of the fluid.

2.3 Optical and hydraulic system configuration

Before calculating the velocity of a fluid, it is necessary to configure the hydraulic and optical systems. In this research a volumetric flux on a F550 rotameter with its valve at 2 to 5 LPM was configured. Also, the longitude between to laser beam references was at 0.12 m and 0.33 m.

3. Results

Three different configurations were used to measure the velocity of the fluid. First (2 to 4 LPM, 0.12 m and variable power on the laser using 2 batteries connected on serial way generating 8.4 V), second (2 to 5 LPM, 0.12 m and stable power on the laser using the power source), and third (2 to 5 LPM, 0.33 m and stable power on the laser using the power source).

The results of these experiment are shown in Figure 2.

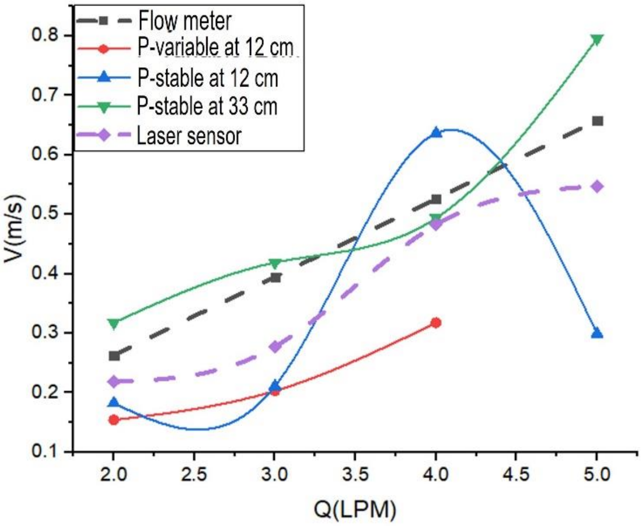

Figure 2. Average velocity vs instantaneous velocity.

The rotameter measures the velocity of the fluid indirectly as it measures the volumetric flux and with the next equation it is possible to calculate the average velocity of the fluid using the volumetric flux from the rotameter [2].

$$v = \frac{Q}{\frac{\pi}{4}D^2} \qquad (2)$$

Where Q = volumetric flux, v = average velocity of fluid and D = diameter of the tube where the rotameter is installed.

The optical sensor measures the velocity of the fluid in a direct way, as it measures the instantaneous velocity of the fluid. Using the instantaneous velocity, it is possible to calculate the average velocity of the fluid using the equation:

$$v_{avg} = \frac{vi_1 + vi_2 + vi_3 \ldots + vi_n}{n} \qquad (3)$$

Where v_{avg} = average velocity of the fluid, $vi_1 + \cdots + vi_n$ = instantaneous velocity of the fluid and n = number of instantaneous velocity measured.

In Figure 2, the black dashed line in ascending trend represents the average velocity from rotameter is shown in the Figure 2. The green, blue and red curves represent the instantaneous velocity taken by optical sensor in three different experiments as mentioned above. The characteristic of the flux measured is always turbulent, for this reason in the graph it is possible to observe the curves with illogical way. Finally, the purple curve represents the average velocity from the green, blue and red curves is similar to the average velocity from rotameter.

3.1 Conventional device and optical sensor uncertainty.

The errors generated from convectional devices measurement were mentioned in the introduction of this research; these errors are called uncertainty measurement.

The rotameters used in the hydraulic system interferes with the fluids, these rotameters have got an uncertainty on its measurement at ± 5% [3]. In the same manner, the optical system generate uncertainty on its measurement using the next devices: a chronometer, this is uses to verify the time of the particle propagation through the hydraulic system, a rule, this is uses to measurement the longitude between laser beam reference, and the spectroscopy, this is uses to calculate the interruption time of the laser beam from leaf.

Using the next equation is possible to calculate the uncertainty of the general system and optical sensor. First, on each device is necessary to measure several times, in this research on each device was measurement 50 times, with those data was calculated the standard deviation using the equation 4 and with the equation 5 was calculated the uncertainty of the general and optical system [4] [5].

$$\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \quad (4)$$

Where σ = standard deviation, x = individual measurement on each device, $\bar{x}$ = average of the individual measurement on each device and n = final number of measurement realized.

$$W_R = \sqrt{(w_1)^2 + (w_2)^2 + (w_3)^2 \dots + (w_n)^2} \quad (5)$$

Where W_R = general experimental uncertainty, $w_1 \ldots w_n$ = uncertainty or standard deviation on each device.

The general system was calculated ± 7.08% of uncertainty (hydraulic and optical system) and the optical system was calculated ± 0.43%.

4. Conclusions

- The flux used in this research was always a turbulent flux, although the system could measure the velocity of fluid on laminar and turbulent flux.
- The minimum velocity measured from this optical sensor was at 0.08 km/h and the maximum was at 5.8 km/h.
- The measurement errors generated from conventional device were reduced. The rotameter has got an uncertainty of ± 5% and the optical sensor has got an uncertainty of ± 0.43 %. This is because the optical sensor is not intrusive and calculates the velocity of fluid on a direct way.
- In this research a laser system for measuring the velocity of a fluids was built. Measurement errors generated from conventional devices were reduced with the use of an optical sensor.

5 References

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6 Acknowledgements

The authors appreciate the support from IPN, CIITEC-IPN, CONACYT, Optical Sciences at University of Twente, MexSoc at Southampton University.