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LIQUID FLOW MEASUREMENTS VIA 3-D PIV

G. Papadopoulos, K. J. Hammad
Dantec Measurement Technology, Inc.
777 Corporate Drive
Mahwah, NJ 07430
USA

A novel approach to flow metering is described based on the particle image velocimetry technique. The flow through a round clear pipe was investigated by isolating a plane normal to the stream direction and obtaining the instantaneous velocity information of tracer particles in the plane. A stereoscopic arrangement was used to obtain all three components of velocity. Integration of the streamwise component over the cross-sectional area of the pipe gave the instantaneous flow rate through the pipe. The benefits and features of this novel approach to flow metering are discussed within the content of measurements performed at several flow rates.
Keywords: Stereo-PIV, pipe flow, metering, image-based velocimetry

1 INTRODUCTION

The benefit of non-intrusiveness has pushed forward the development of optical diagnostic methods as viable tools in many engineering applications, from basic research to applied measurements. Further development efforts will continue in the coming century and the trend is expected to grow as the necessity for measurements increases, partially fuelled by the increased need for quality and robustness by industry related concerns. Catering to such concerns requires the adaptation of advanced optical diagnostic methods to industrial applications, and the present paper discusses the results of an effort to do as such.

Particle image velocimetry (PIV) is a robust optically-based measurement technique, which since its introduction a little more than ten years ago has received extensive attention and utilisation.[1-3] It is a robust quantitative technique that relies on the basic principle of distance over time to yield velocity, typically along a two-dimensional slice within a particular flow. The specifics of the technique are covered in a latter section of the paper. PIV differs from the laser Doppler anemometry (LDA) technique, in that with PIV the simultaneous velocity at many points in the flow are determined, while with LDA only one point in the flow is probed.

This benefit of PIV over LDA makes it ideal for flow metering implementation, since in such applications the bulk velocity of the flow through a conduit having certain cross-sectional characteristics is of primary interest. One would ideally like to obtain the bulk velocity value by integrating the streamwise component of velocity along the conduit's cross-section, and the simultaneous spatially resolved velocity information generated by PIV is very suitable for performing such a task.

A wide variety of flow-metering techniques have been developed and used in the past. The most common ones are the differential-pressure type meters, such as, orifice meters [4], venturi tubes and flow nozzles [5], pitot tubes and laminar flow meters [6]. Differential-pressure type meters have gained wide acceptance due to their low expense, simplicity and ruggedness. Other commonly used flow metering devices include momentum type flow meters, which require the placement of a rotating propeller wheel in the flow conduit [7]. The flowing fluid interacts with the wheel and results in an angular velocity that can be related to the average flow rate within the conduit. The rotational velocity of the wheel is typically captured by the frequency of passage of the blade tip past a coil pickup placed on the pipe wall. Obvious disadvantages of differential-pressure and momentum type flow metering techniques include: 1) accuracy and reliability is significantly dependent on flow and fluid effects, such as, profile, swirl, pulsations, and the presence of contaminants [8]; 2) sensitivity to upstream and downstream meter-tube conditions such as roundness, straightness, smoothness and length [9]; 3) intrusiveness; 4) they, quite often, result in substantial additional pressure-loss; and 5) they require flow conditioning devices which control the distribution of the flow into the meter, therefore, additional space and cost [9,10].

Other flow metering techniques include rotameters, acoustic [11], magnetic, thermal, vortex shedding [12] and coriolis-acceleration flow meters.

Successful implementation of any of the above mentioned flow metering techniques is contingent upon accounting for the influence of different flow anomalies. Due to the nonlinear nature of the flow phenomenon within each flow meter, accurate predictions of such influences on the performance of different types of flow meters, therefore, requires the design and implementation of expensive and time consuming test experiments [4].

In the present paper, a novel technique that utilizes PIV methodology and technology to measure the velocity along the cross-section of a conduit is presented. The technique relies on the stereoscopic principle of PIV to yield information on all three components of velocity at many points along the cross-section of the conduit. Integration of the streamwise component of velocity is then shown to yield the bulk velocity through the conduit.

2 PRINCIPLES OF PIV

The basic relation of displacement divided by time to yield velocity is the fundamental principle of the PIV technique. The displacement information is provided by seeding particles, which are suspended in the fluid and are assumed to follow the flow. However, unlike earlier particle tracing methods, PIV does not rely on the tracking of individual particles, and hence offers a higher temporal and spatial resolution of the instantaneous flow field. The early application of PIV relied on photographic film technology, but current advances in image-capture using digital technology (charged-coupled devices, or CCD's) has dramatically improved the technique's robustness.

2.1 Planar 2D PIV

Tracer particles in the fluid, either naturally or artificially occurring, are illuminated using a thin light sheet, which is pulsed to freeze the particle motion. The Mie scattering from the particles is recorded, from a direction normal to the light sheet, at two instances in time using a digital camera. The two sequential digital images are then sub-sampled at particular areas via a prescribed interrogation window, and a spatial cross-correlation is performed using fast Fourier transform (FFT) analysis, as described by Willert and Gharib [3]. The separation time between the light pulses is selected so as to have particles displace several pixels within the interrogation area, and at most remain common to both images. A high cross-correlation value is observed where many particle images match up with their corresponding spatially shifted partners, and this is considered to represent the best match of particle images between the sequential recordings.

The displacement vector of the cross-correlation peak from the center (origin) of the two-dimensional interrogation window denotes the average distance travelled by the particles within the interrogation area. Accurate estimation of the displacement vector to sub-pixel resolution is performed by locally fitting the two-dimensional array of correlation values in the vicinity of the peak. The absolute displacement vector is then calculated from a calibration of the magnification factor between the pixel domain of the digital recording device and the physical field of view. Finally, division of the displacement vector, determined for each interrogation area along the entire pixel domain, by the time separation between the two sequential laser pulses yields the velocity vector field in the physical area under investigation.

2.2 Stereo-PIV for Planar 3D Measurements

In stereo-PIV two cameras are used to image the same flow field from different angles instead of a single camera viewing from a normal direction, as illustrated in Figure 1. Stereo-PIV takes advantage of the parallex error that is inherent in 2D planar PIV measurements, an error that comes about from imaging the projected trajectory of particles in the plane of the laser light sheet, instead of the actual three-dimensional trajectory. By imaging particle displacements from two distinctly different viewing angles, distinct projected trajectories for the same group of particles are determined, as shown in Figure 1.

To properly view the plane illuminated by the light sheet using the stereo-PIV arrangement, the camera's back-plane (i.e. the CCD-chip) must be tilted to properly focus the camera's entire field of view. A special optical arrangement is required to meet the so-called Scheimpflug condition, which states that the image, lens and object plane must be collinear for the camera images to be properly focused in the entire field of view [13].

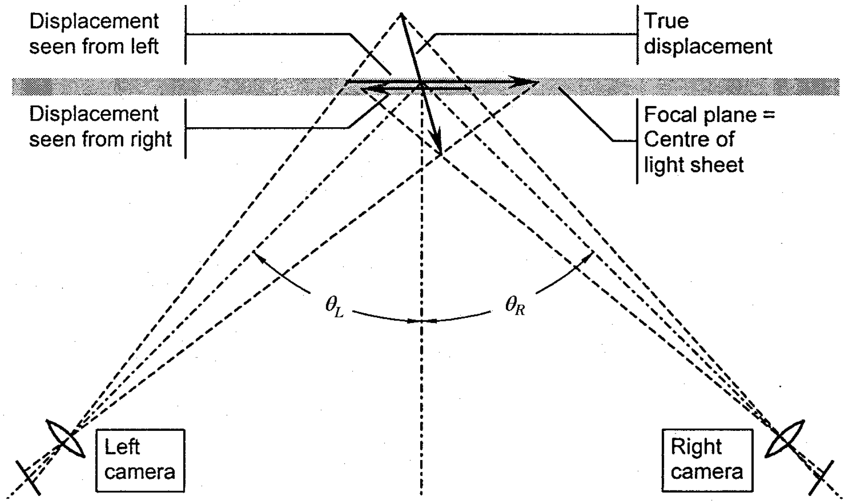

Figure 1 Principle of stereo-PIV (displacement enlarged for better visibility).

The two-dimensional projected trajectories are combined using a numerical model describing how each camera images the flow field to determine the actual three-dimensional trajectory of the group of particles within the laser sheet. Early work for evaluating the parameters of such a model was based on exact assessment of the geometrical arrangement of the two cameras and optical configuration, but current methods rely on imaging a well defined calibration target that is used to imitate the out-of-plane motion. The latter method offers a robust way of calibrating the system, one that easily takes into account distortions caused by index-of-refraction effects, and thus is the preferred way of current stereo-PIV measurements.

Construction of the three-dimensional velocity map means that true particle displacements (*Dx, Dy, Dz*) are extracted from a pair of two-dimensional displacements (*Dx, Dy*) corresponding to the vector results obtained from the left and right cameras. This means that a system of 4 equations in 3 unknown needs to be solved, and depending on the approach, the equations may be linear or non-linear, as discussed by Morck et al. [14].

In the present application of stereo-PIV, significant non-linearities due to complex refractions arising from index-of-refraction differences between air and liquid interfaces require that a polynomial imaging model is used, as suggested by Soloff et al. [15].

3 EXPERIMENTAL SETUP

3.1 Test Configuration

A schematic of the experimental setup and flow loop is shown in Figure 2. The test section was a cast acrylic tube with a nominal outside diameter of 1 ¾ -inches and wall thickness of 1/8-inches. The inside diameter of the tube was measured at $D = 37.2 \pm 0.5$ mm. The working fluid was water at ambient conditions, which was pumped from a supply tank featuring inter-connected feed and return sections. A valve allowed operation of the flow loop under open or closed circuit conditions. A turbine flow meter was located prior to the test section and used to measure the bulk flow through the loop.

To minimize index-of-refraction effects when imaging the test section using the stereo arrangement, the test section was enclosed within a clear triangular enclosure, as shown in Figure 2, filled with glycerin. In this manner, the cameras imaged the test plane through a Plexiglas flat section, which was nearly normal to the view direction.

Artificial seeding of the flow was necessary to successfully implement the measurement methodology discussed herein. In the present arrangement, 10-µm silver coated hollow glass spheres were used.

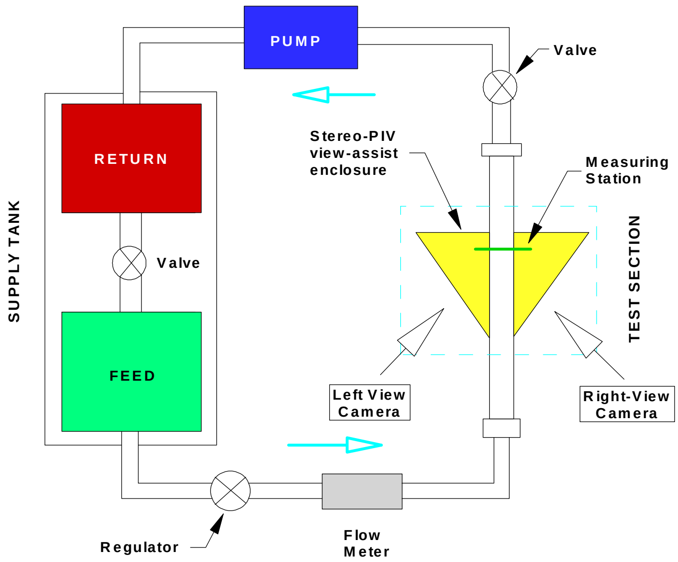

Figure 2 Schematic of flow loop.

3.2 Stereo-PIV System

A commercial PIV system was used consisting of a laser illumination source, a pair of digital cameras, and dedicated hardware and software for data analysis. The illumination source was a 50-mJ, double-cavity, mini-Nd:Yag laser operating at a wavelength of 532-nm and a pulsation frequency of 15 Hz. The laser head was mounted on a bread-board along with the pipe test section and cameras. Adjustable sheet forming optics mounted at the exit portal of the laser head generated a light sheet, which was reflected 90-degrees using a mirror cube, as seen in Figure 3. The light sheet was directed vertically upward and positioned normal to the stream direction.

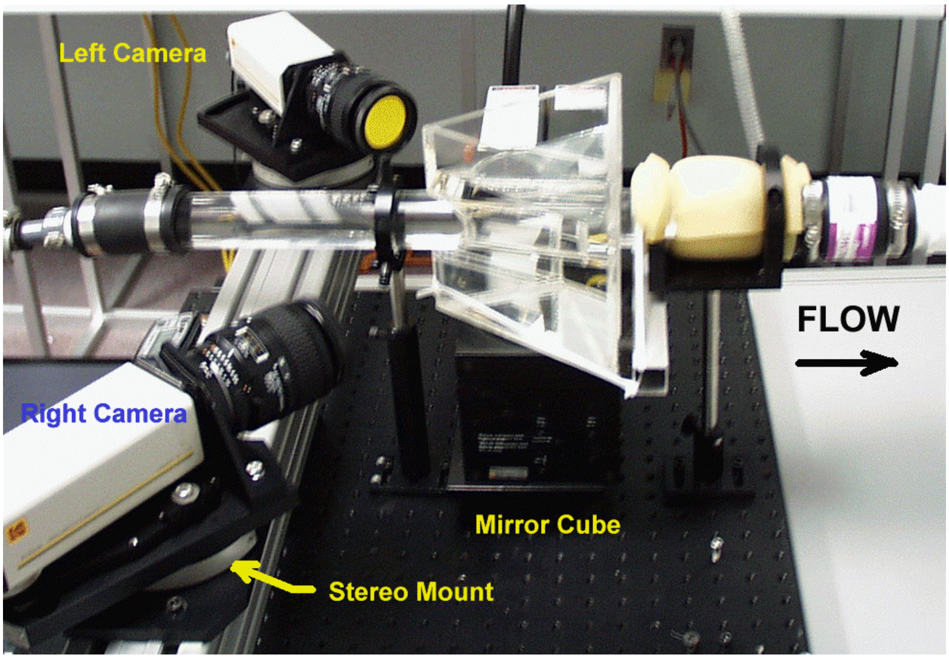

Figure 3 Photograph of experimental setup.

A pair of 8-bit, double-frame CCD cameras having a resolution of 1008 x 1018 pixels were used to image the Mie scattered light from tracer particles illuminated by the laser sheet. The frame-straddling technology of such cameras allowed for the use of cross-correlation methods when determining the velocity vector information without image order ambiguity. Each camera was fixed on a special mount that allowed for the rotation of the camera body with respect to the lens so as to meet the Scheimpflug condition. A standard 60-mm Nikkor lens was used.

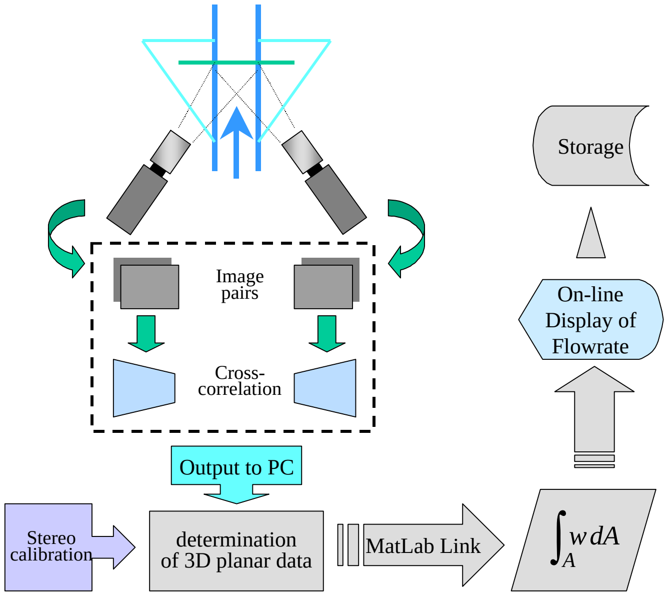

Figure 4 Processing scheme used for on-line determination of flow rate.

Processing of the pair of images from each camera was done via dedicated hardware for on-line correlation analysis by means of FFT-based algorithms implemented using programmable electronics. The correlator was housed inside a processor unit, which also contained a synchronization board for controlling laser and camera activation sequences, and a 12-bit analog-to-digital converter for sampling the voltage output from the turbine flow meter simultaneously with image capture.

Figure 4 shows the processing scheme used to determine the instantaneous flow rate through the test section. Once image pairs were cross-correlated to yield two-dimensional vector information of the respected projected motion of particles illuminated by the laser sheet, the data was passed to a personal computer where predetermined calibration parameters were used to combine the information and generate the three-dimensional velocity information along the cross-plane. A dynamic link to a MatLab script was subsequently used to integrate the streamwise velocity component along the cross-section and produce a single value representing the flow rate across the test section. The instantaneous flow was displayed on-line, as well as stored for further statistical interpretation.

3.3 Calibration

A special calibration target squarely populated by black dots on white background was cut to size to fit into the test section. The target was mounted on a flat disk, and was placed at the measurement station, as defined by the laser sheet. The center-to-center spacing of the dots was measured prior to insertion into the test section and determined to be S = 1.35 mm ± 0.01 mm.

To properly calibrate the stereo imaging arrangement, the test section was filled with water while the target was in place. The target was moved to 5 positions about the z = 0 location (z = -1, -0.5, 0, 0.5, 1 mm) and imaged at each position. The positional accuracy of the target was a key factor in the absolute accuracy of the stereo-PIV technique, and in the present calibration, the estimated uncertainty in locating the target was ± 0.1 mm.

A typical pair of calibration images is shown in Figure 5. Significant distortion due to the off-normal viewing arrangement of the stereo-PIV arrangement is observed. Image distortion resulting from the curved pipe walls and large refractive index mismatch between air and water was minimised by using the triangular enclosure filled with glycerin. To properly accommodate the distortion, a third-order polynomial imaging model was used for the calibration algorithm [14].

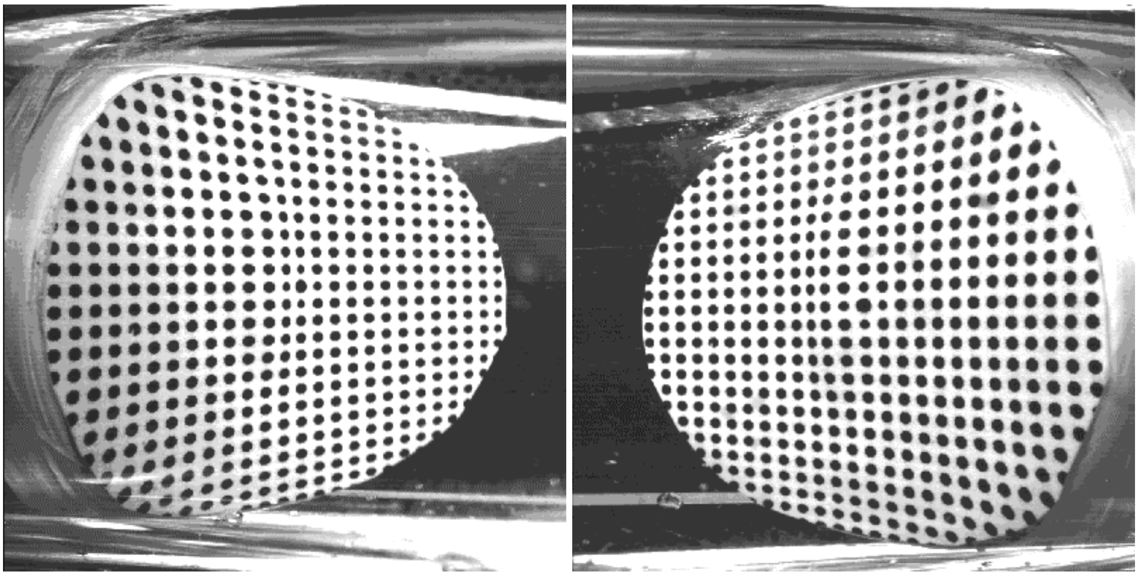

Figure 5 Calibration target images at location *z* = 0 mm: left and right views from corresponding cameras.

3.4 Flow Conditions

Prior to initiating the evaluation phase of the investigation, the in-line turbine flow meter was calibrated by running the loop under open-circuit conditions, and moving fluid from the feed section of the supply tank into the return section. The height of fluid pumped into this section was timed to establish an accurate flow rate reference. Results from the turbine flow meter calibration are shown in Figure 6. It was observed that the turbine flow meter under-estimated the flow rate in the range of flows investigated by about 7%. The uncertainty in subsequent measurements using this turbine flow meter was less than 1% of the reading, according to manufacturer's specifications.

Application of the stereo-PIV flow meter methodology was evaluated under steady flow conditions, with the flow loop being operated in closed-circuit mode. Several flow rates in the range of Q = 4.7 lpm to Q = 6.5 lpm were investigated. The results of these measurements are presented in the next section.

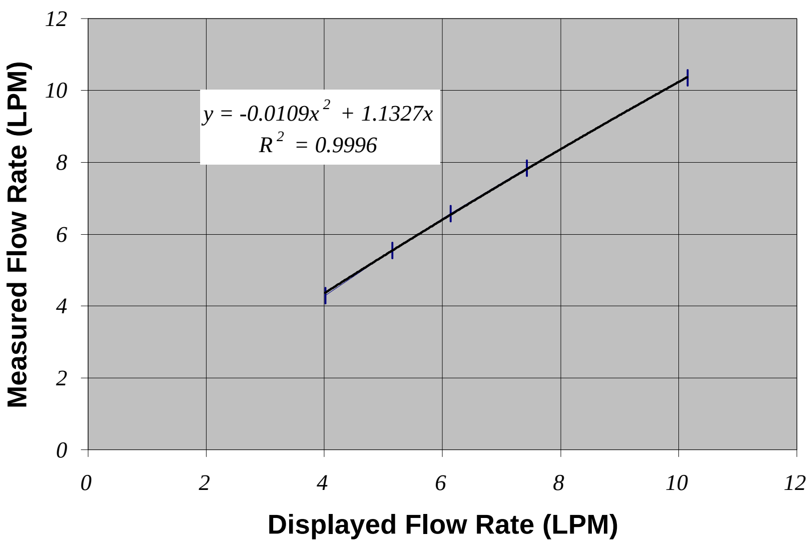

Figure 6 Flow meter calibration using volume-over-time method.

4 RESULTS

A typical instantaneous measurement of all three components of velocity along the pipe cross-section, as determined by the stereo-PIV technique, is shown in Figure 7. In the figure, the magnitude of the out-of-plane component of velocity, *w*, is depicted by the meshed geometry, while the contour plot shows the in-plane magnitude of the remaining two components of velocity. Typical steady flow conditions do not necessarily imply constant distributions from one instant to the next, and the results in Figure 7 depict this behavior when comparison is made to time-averaged distributions of velocity obtained after 94 such instantaneous representations (Figure 8).

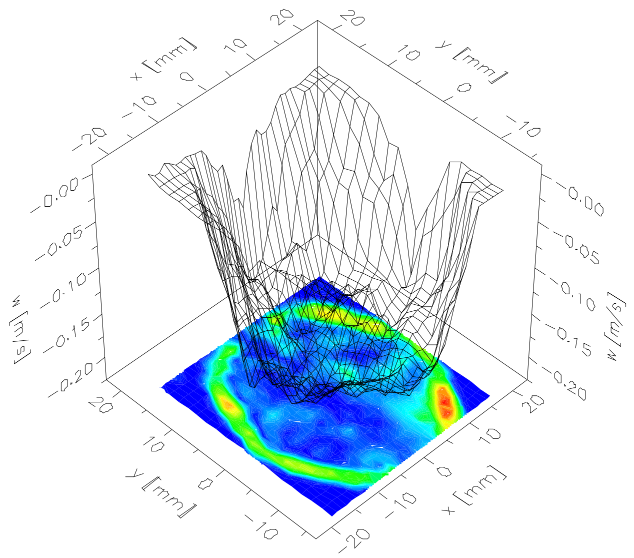

Figure 7 Instantaneous three-dimensional velocity field along the pipe cross-plane: meshed geometry represents out-of-plane velocity component magnitude; color-flooded contour shows in-plane velocity magnitude distribution.

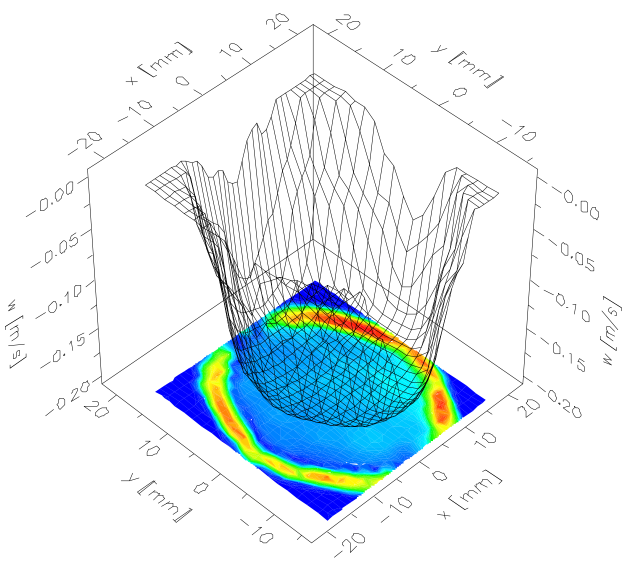

Figure 8 Time-averaged three-dimensional flow along the pipe cross-plane from 94 instantaneous realizations: flow rate condition is the same as in Figure 7.

Comparison of absolute flow rates determined using the stereo-PIV approach with the output of the turbine flow meter are listed in Table 1. The flow rates obtained using the stereo-PIV approach are higher, but it should be pointed out that the two match within the uncertainty in the measurements. The large uncertainty in the stereo-PIV measurement comes about mostly from the calibration aspect of the technique, specifically the uncertainty with which the calibration target was moved. This uncertainty was estimated at ± 0.1 mm, and this value is rather large within the overall range of motion of the target. If the systematic effect of this error is removed by using the flow rate measured by the turbine flow meter in CASE I as an absolute reference, then the average flow rate determined by subsequent measurements using the Stereo-PIV technique in CASE II and III falls within 1% to 2% of the average reading indicated by the turbine meter.

Table 1 Results from time-averaged flow rate measurements using the stereo-PIV methodology.

CASE	Flow Rate (LPM)		Error
	Turbine meter	Stereo-PIV meter	$\frac{Q_{SPIV} - Q_{Turb}}{Q_{Turb}}$
I	4.71 ± 0.20	5.64 ± 0.75	19%
II	6.09 ± 0.25	7.17 ± 0.75	17%
III	6.42 ± 0.25	7.39 ± 0.75	15%

5 CONCLUSIONS

A novel approach to flow rate metering using the stereo particle image velocimetry technique has been demonstrated. The stereo-PIV technique was successfully applied to obtain flow rate measurements through a round clear pipe. A comparison with measurements of the same flow using an in-line, turbine flow meter was satisfactory and established the validity of the proposed flow metering technique. The accuracy of the stereo-PIV based flow-metering approach was found to be largely dependent on the execution of the calibration process. Specifically, the positional accuracy of the calibration target was determined to be the key factor in the absolute accuracy of the stereo-PIV technique. This error is a systematic one, and can be largely eliminated by calibrating the system at a known flow rate before actual implementation.

Contrary to traditional flow metering techniques, the new PIV-based technique does not require flow conditioning and does not affect the overall pressure drop characteristics of the flow loop. Further, stereo-PIV based flow metering is insensitive to, typically very limiting factors, such as flow regime, flow profile and degree of swirl, conduit straightness, smoothness, length and roundness.

More detailed work is planned that will address the influence of spatial resolution and temporal response characteristics on the precision and accuracy of flow metering using the stereo-PIV technique.

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AUTHOR(S): Dr. George Papadopoulos, Dr. Khaled J. Hammad, Dantec Measurement Technology, Inc., 777 Corporate Drive, Mahwah, NJ, 07430, USA, phone 1-201-512-0037. E-mail: george.papadopoulos@dantecmt.com, khaled.hammad@dantecmt.com .