Video Article

Echo Particle Image Velocimetry

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Abstract

The transport of mass, momentum, and energy in fluid flows is ultimately determined by spatiotemporal distributions of the fluid velocity field.[1] Consequently, a prerequisite for understanding, predicting, and controlling fluid flows is the capability to measure the velocity field with adequate spatial and temporal resolution.[2] For velocity measurements in optically opaque fluids or through optically opaque geometries, echo particle image velocimetry (EPIV) is an attractive diagnostic technique to generate "instantaneous" two-dimensional fields of velocity.[3,4,5,6] In this paper, the operating protocol for an EPIV system built by integrating a commercial medical ultrasound machine[7] with a PC running commercial particle image velocimetry (PIV) software[8] is described, and validation measurements in Hagen-Poiseuille (*i.e.*, laminar pipe) flow are reported.

For the EPIV measurements, a phased array probe connected to the medical ultrasound machine is used to generate a two-dimensional ultrasound image by pulsing the piezoelectric probe elements at different times. Each probe element transmits an ultrasound pulse into the fluid, and tracer particles in the fluid (either naturally occurring or seeded) reflect ultrasound echoes back to the probe where they are recorded. The amplitude of the reflected ultrasound waves and their time delay relative to transmission are used to create what is known as B-mode (brightness mode) two-dimensional ultrasound images. Specifically, the time delay is used to determine the position of the scatterer in the fluid and the amplitude is used to assign intensity to the scatterer. The time required to obtain a single B-mode image, t, is determined by the time it take to pulse all the elements of the phased array probe. For acquiring multiple B-mode images, the frame rate of the system in frames per second $(fps) = 1/\delta t$. (See 9 for a review of ultrasound imaging.)

For a typical EPIV experiment, the frame rate is between 20-60 fps, depending on flow conditions, and 100-1000 B-mode images of the spatial distribution of the tracer particles in the flow are acquired. Once acquired, the B-mode ultrasound images are transmitted via an ethernet connection to the PC running the PIV commercial software. Using the PIV software, tracer particle displacement fields, $D(x,y)$[pixels], (where x and y denote horizontal and vertical spatial position in the ultrasound image, respectively) are acquired by applying cross correlation algorithms to successive ultrasound B-mode images.[10] The velocity fields, $u(x,y)$[m/s], are determined from the displacements fields, knowing the time step between image pairs, ΔT[s], and the image magnification, M[meter/pixel], *i.e.*, $u(x,y) = MD(x,y)/\Delta T$. The time step between images $\Delta T = 1/fps + D(x,y)/B$, where B[pixels/s] is the time it takes for the ultrasound probe to sweep across the image width. In the present study, M = 77[μm/pixel], fps = 49.5[1/s], and B = 25,047[pixels/s]. Once acquired, the velocity fields can be analyzed to compute flow quantities of interest.

Video Link

The video component of this article can be found at http://www.jove.com/video/4265/

Protocol

1. Create a Measurable Flow

1. EPIV validation measurements will be demonstrated in pipe flow of a glycerin water solution (50% glycerin - 50% water). A schematic of the experimental setup is shown in **Figure 1**.
2. Hollow glass spheres with a nominal diameter of 10 μm are added to the fluid at a concentration of approximately 17 weight parts per million. The hollow glass spheres serve as ultrasound contrast agents, and their size and density are chosen such that they passively follow the fluid flow.[10]
3. A fixed voltage is supplied to the pump to introduce a known flow rate. The flow rate is chosen such that $U << \Delta X/\delta t$, where U is the mean velocity in the pipe, ΔX is the linear length of the EPIV measurement volume, and δt is the time step between images, *i.e.*, the flow need be "slow" compared to the fps of the ultrasound system.[3]

2. Calibrate the Ultrasound

1. Mount the ultrasound probe to the exterior pipe wall. A water based topical gel is applied to the ultrasound probe to minimize loss of transmission of the ultrasound beam between the probe face and the pipe wall.
2. Power on the ultrasound machine. A live stream of ultrasound images begins automatically once all systems load.
3. Set the image depth using the *Depth Control* knob on the control panel of the ultrasound machine.
4. Set the total image gain using the *2D Gain* knob on the control panel of the ultrasound machine.
5. Adjust the *Time Gain Compensation (TGC)* sliders to attenuate scatter from the pipe walls and to compensate for depth related attenuation of the ultrasound signal.
6. The *image width, focus, probe operating frequency*, and *frame rate* are adjusted using the assignable control knobs. These four knobs, located on the top left of the control panel, vary according to the mode in which the system is running. In 2D mode (as presently used), from left-to-right the knobs correspond to *width, focus, frequency*, and *frame rate*, respectively. Note that owing to the fundamental principles of ultrasound imaging[9], these four parameters are inherently coupled. Consequently, for a given ultrasound image scan (*i.e.*, an EPIV experiment) there is a trade-off between spatial and temporal resolution.
7. See **Figure 2** for a representative ultrasound image of pipe flow seeded with 10 µm hollow glass spheres. Note that due to limited lateral resolution, the glass spheres are smeared in the lateral direction and appear as ellipsoids in the image.

3. Data Collection

1. Press the *New Exam* button on the ultrasound control panel to start a new experiment.
2. Create a new "patient" by entering Pipe Flow in *Last Name* and todays date in *First Name* and the test number in *Patient ID*.
3. Following creation of the "patient", an ultrasound scan begins until the preset maximum of between 1000-1500 images is reached, after which a new scan loop begins. Pressing the *Freeze* button on the ultrasound control panel twice will restart the scan at anytime prior to reaching the maximum preset number of images.
4. Once a good set of ultrasound images has been acquired (*i.e.*, sharp seed particle images and sufficient seed particle density), press the Freeze button on the ultrasound control panel to stop image acquisition.
5. Press the *Cineloop* button on the ultrasound control panel. Select the set of ultrasound images to be analyzed using the *First Cycle* knob on the ultrasound control panel to select the first image in the set, and the *Last Cycle* knob to select the last image in the set.
6. Press the *Image Store* button on the ultrasound control panel to save the selected set of ultrasound images.
7. Press the *Archive* button on the ultrasound control panel and use the mouse cursor to select *End Exam*. This will prompt the user to select images or cineloops to save to the local hard drive. Select the cineloop(s) of interest then exit the exam.
8. Press the *Archive* button on the ultrasound control panel and use the mouse cursor to first select *More* and then select *Disk management. Disk management* will transfer the saved cineloop(s) to the PC running the PIV software.

4. Converting Filetype

1. An ultrasound image is stored as a digital imaging communications in medicine (DICOM) file type on the ultrasound machine. In order to be opened and read by the PIV software, the DICOM files must be converted to picture files. Presently, a Matlab script running *DICOM2JPG.m* is used to convert the DICOM files to joint photographic experts group (JPEG) file type.
2. The JPEG ultrasound images are then analyzed using DaVis software from LaVision.

5. Computing Displacement Fields, *D(x, y)*, Using DaVis

1. Double mouse click on the *DaVis* icon on the PC. Select *New Project*. Select *PIV*.
2. Select *Import Images* in the toolbar, and choose *Import via Numbered Files*. In the pull-down menu, locate the folder where the JPEG ultrasound images are stored, and double click on the first image of the set. This will import all ultrasound images in this numbered set.
3. Typically an image mask will be defined to isolate the region of interest (ROI) in the ultrasound image to be processed. For pipe flow, the mask is used to define the ROI between the pipe walls (*i.e.*, the fluid).
4. Go to the main control panel in DaVis, select the tab located under *Current Project* containing the imported images, and select the tab labeled *Batch Processing*. This enables the vector processing window of DaVis for batch processing of the imported ultrasound images.
5. From the operations list, using the *PIV-Time-Series* tree, select *vector calculation parameters*, and choose the parameters to be used for vector processing. If a mask is used, check the box *Data Range = use masked area* in the *vector calculation parameter* menu. Note that optimal selection of *vector calculation parameters* is dependent on flow geometry, flow properties, image resolution, tracer particle density, and desired quantitative flow analysis.[10]

   For the pipe flow measurements, the parameters that have typically yielded the best results are multipass with decreasing interrogation size of 32 x 32 pixel^2 to 8 x 8 pixel^2, with an overlap of 50%. Relative vector range restriction was set to ±*all(window size/2)* and absolute vector range restriction was set to ±5 pixels. Lastly, a 3 x 3pixel^2 median filter was used to suppress noise and smooth the vector fields.
6. On the left of the *batch processing* screen, select the total amount of images to be processed and select *start processing*. This will compute the displacement field, *D(x,y)*, between successive ultrasound images using cross-correlation algorithms.

6. Analyzing Vector Fields

1. For post-processing and data analysis, the EPIV vector fields are exported from DaVis as *.txt* files. This is achieved by selecting the vector displacement branch under the JPEG image branch in the project screen. In the toolbar, select the *Export* tab, select file type ASCII *.txt*, choose/create an export folder, and select *Export*.
2. The exported vector fields are named *Bxxxxx.txt*, where 00001≤ xxxxx ≤ 99999, with *B* denoting buffer. Each file contains four data columns: (1) x-location of the vector in the image, (2) y-location of the vector in the image, (3) x-component of displacement (*i.e.* streamwise displacement), (4) y-component of displacement (*i.e.*, wall-normal displacement). The *Bxxxxx.txt* files are opened and processed in MATLAB to first compute the velocity field, by knowing the time step between image pairs, *ΔT[s]*, and the image magnification, *M*[meter/pixel], *i.e.* $u(x,y) = MD(x,y)/\Delta T$,. The time step between images $\Delta T = 1/fps + D(x,y)/B$, where *B*[pixels/s] is the time it takes for the ultrasound probe to sweep across the image width. In the present study, $M = 77$[μm/pixel], $fps = 49.5$[1/s], and $B = 25{,}047$[pixels/s]. Next, ensemble average velocity vector fields, wall-normal profiles of mean velocity, among other flow quantities of interest are computed. (See section Representative Results.)

Representative Results

An instantaneous echo particle image velocimetry (EPIV) vector field is shown in **Figure 3**. The vector plot shows velocity vectors every fourth column, and the background color contour map corresponds to velocity magnitude. An ensemble average vector plot averaged over 1000 instantaneous EPIV vector plots is shown in **Figure 4**. Consistent with pipe flow, the velocity vectors are primarily in the streamwise direction, the largest velocities occur at the pipe centerline, and the velocities decrease to zero at the pipe walls. The root-mean-square (rms) velocity magnitude fluctuation is shown in **Figure 5**. Since in Hagen-Poiseuille flow, the rms velocities should be identically zero, the non-zero rms velocities provide a measure of the noise in the EPIV measurements. The high rms values near the upper wall results from strong reflection and refraction of the ultrasound beam from the pipe wall that produce high image intensities in this region (see **Figure 2**). These high intensities near the walls obscure particle intensities leading to measurement errors. The wall-normal profile of mean streamwise velocity computed by averaging the ensemble-averaged vector plot along the rows (horizontal direction) is plotted in **Figure 6**. The solid black line is the expected mean streamwise velocity profile for Hagen-Poiseuille (laminar pipe) flow for the given experimental conditions. The agreement between the EPIV measurements and the expected Hagen-Poiseuille profile is best near the pipe centerline and worst near the pipe walls, with the largest deviations occurring near the top wall. We are presently working on methods to reduce the ultrasound reflection and refraction at the pipe wall and to improve the near-wall EPIV measurements.

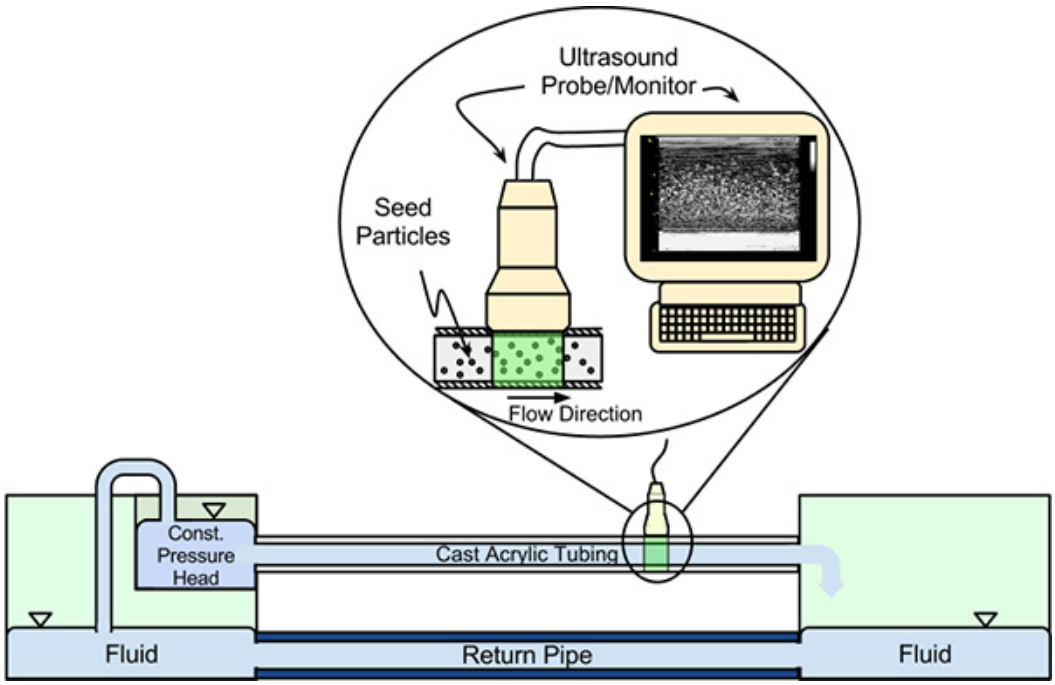

Figure 1. Schematic of the experimental setup. An aquarium pump drives the fluid (seeded with 10 μm glass microspheres) in a closed loop piping system. The linear ultrasound probe is affixed to the exterior pipe wall and transmits ultrasound waves through the pipe and receives echoes reflected from the 10 μm glass microspheres and the pipe walls. The ultrasound machine processes the reflected ultrasound waves to form an ultrasound B-mode image. The ultrasound B-mode images are exported to a PC running commercial PIV software.

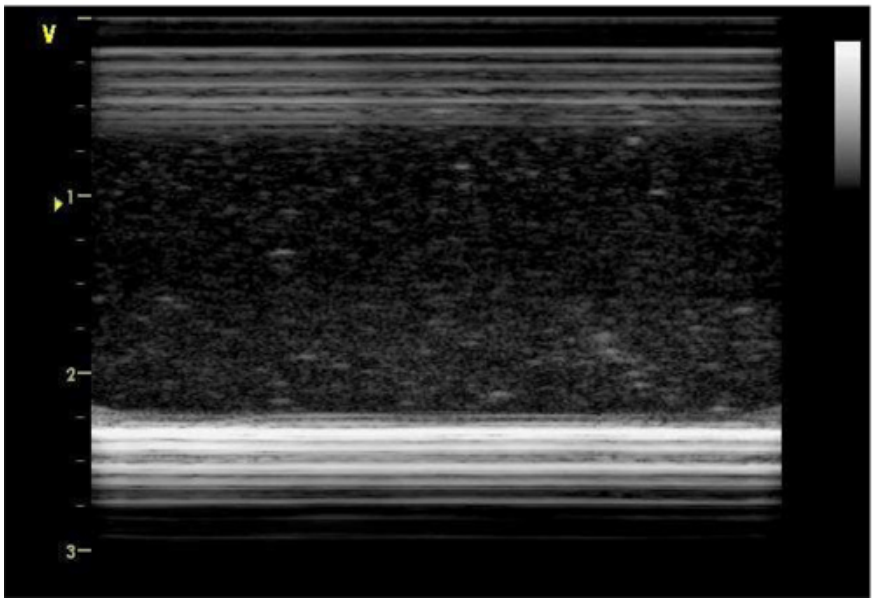

Figure 2. Raw ultrasound B-mode image of pipe flow. The high intensity band of lines at the top and bottom of the image correspond to the pipe wall and the ellipsoids interior to the wall correspond to the 10 m hollow glass microspheres.

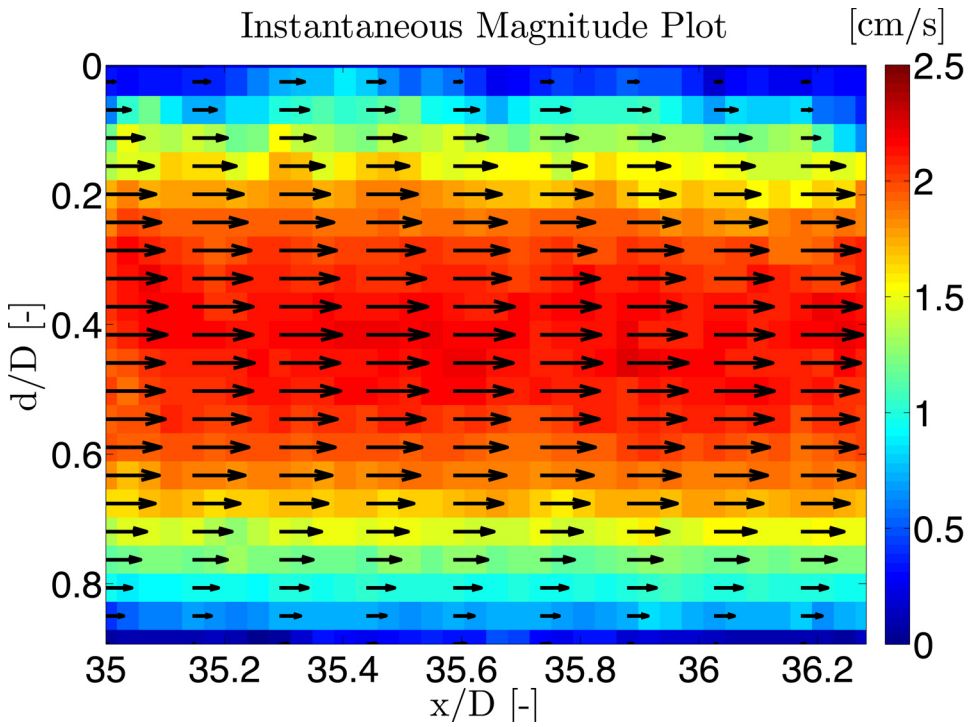

Figure 3. An instantaneous vector plot showing vector arrows every fourth column. The background color contour map corresponds to velocity magnitude. D is the pipe diameter, x is the streamwise position measured from the pipe inlet, and d is the radial position measured from the upper wall.

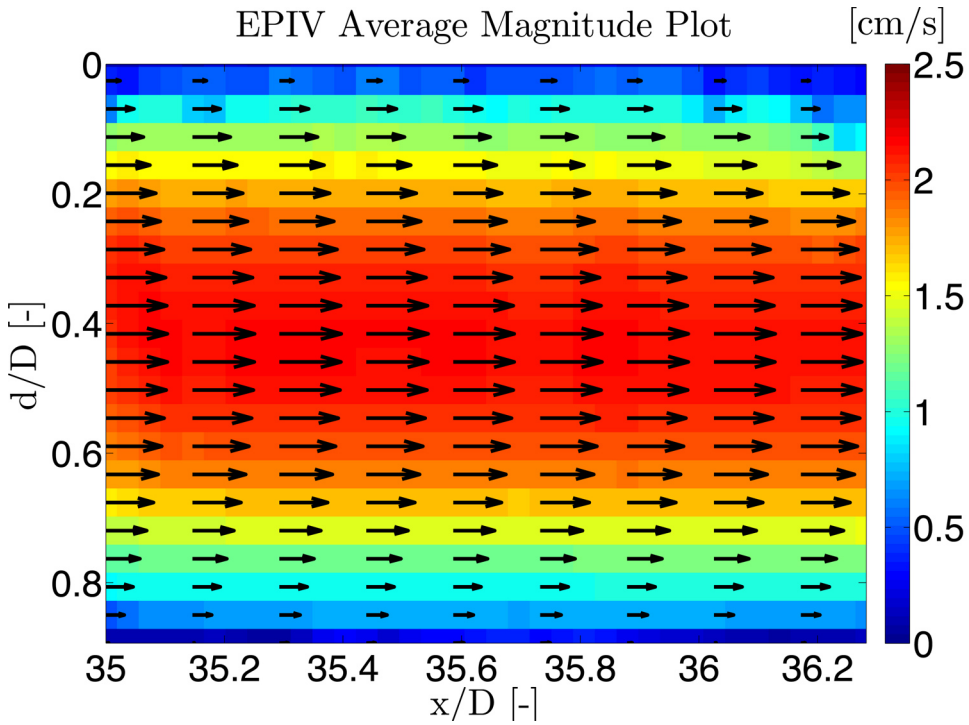

Figure 4. Ensemble average vector plot averaged over 1000 instantaneous EPIV vector plots. The vector plot shows velocity vectors every fourth column, and the background color contour map corresponds to velocity magnitude. Consistent with pipe flow, the velocity vectors point in the streamwise direction, the largest velocities occur at the pipe centerline, and the velocities decrease to zero at the pipe walls.

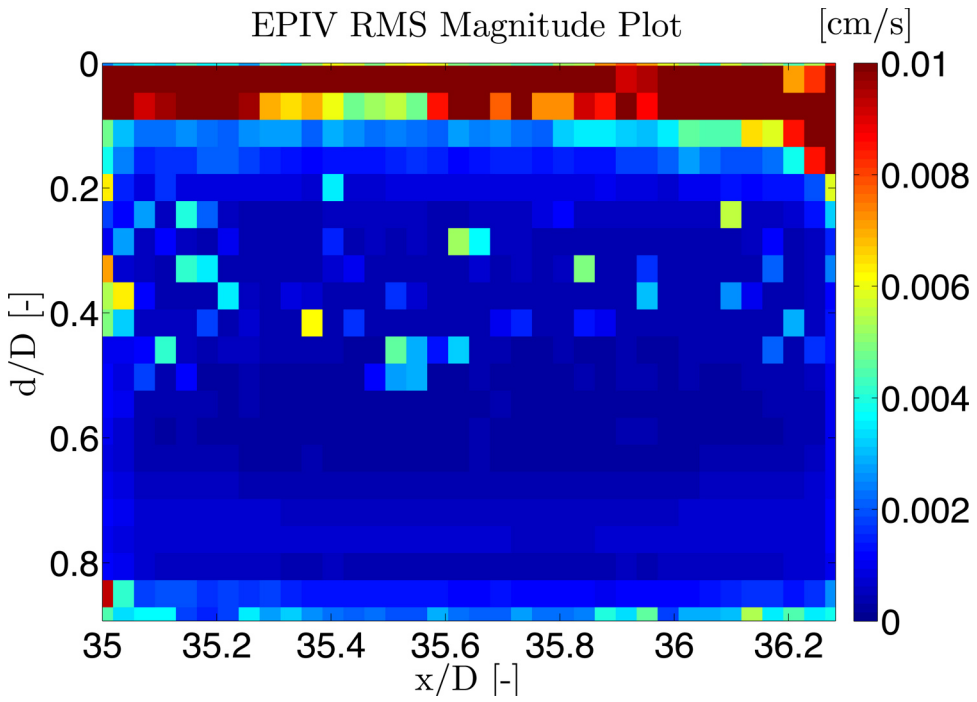

Figure 5. Contour plot of the root-mean-square (rms) velocity fluctuation computed over 1000 instantaneous EPIV vector plots. In Hagen-Poiseuille flow, the rms velocity fluctuations provide a measure of noise in the EPIV measurements.

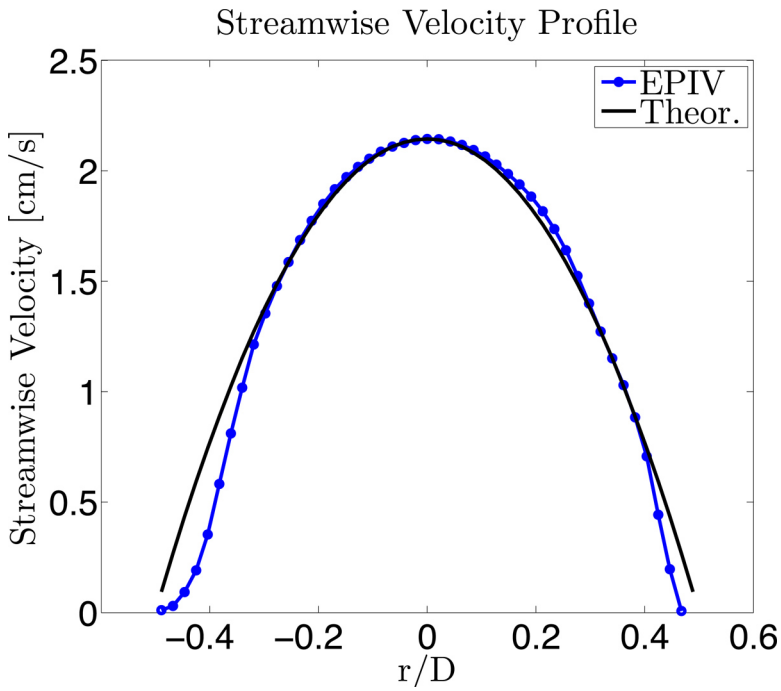

Figure 6. The experimental measured mean streamwise velocity profile computed from the ensemble-averaged EPIV vector field shown in **Figure 4**. The solid black line is the theoretically expected profile for a Hagen-Poiseuille flow with the same volumetric flow rate as measured experimentally. The radial position measured from the pipe centerline is denoted by r, where the upper wall corresponds to r/D = -0.5. Differences between the experimental profile and the expected profile illustrate the difficulty of near-wall EPIV measurements.

Discussion

The operating protocol for an echo particle image velocimetry (EPIV) system capable of acquiring two-dimensional fields of velocity in optically opaque fluids or through optically opaque geometries was described. Practical application of EPIV is well-suited for the study of industrial and biological flow systems, where the flow of opaque fluids occurs in a great many application. The particular system presented here was purposefully built to study the flow properties of liquefied biomass fluids used in the production of lignocellulosic ethanol. The capabilities of EPIV were demonstrated using representative measurements in pipe flow. In particular, mean and rms velocity profiles were computed from EPIV vector fields, Hagen-Poiseuille (laminar) pipe flow was shown to be measurable and quantifiable. The limitations of EPIV are the inherently low frame rates (limited by the imaging capabilities of the commercial ultrasound system) and low spatial resolution, which limits the range of velocities and transient flow behavior that can be measured. Lastly, although we have strived to make the article self-contained, the user manuals for the commercial ultrasound machine[7] and the PIV software[8] should be consulted for completeness. The reader is also referred to [9] and [10] for a comprehensive review of ultrasound imaging fundamentals and particle image velocimetry, respectively.

Disclosures

Authors have nothing to disclose.

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