

# Validation of Micro PIV Measurements in PDMS Micro-channel Flow Geometries

R. J. Adrian, E. Yamaguchi  
Department of Theoretical and Applied Mechanics  
University of Illinois, Urbana, Illinois 61801

P. Vanka, T. Plattner  
Department of Mechanical and Industrial Engineering  
University of Illinois, Urbana, Illinois 61801

W. Lai  
TSI, Inc., St. Paul, Minnesota 55164

## Abstract

Micro-particle image velocimetry achieves resolution as small as  $1 \mu\text{m}^3$  by microscopically imaging fluorescent particles (Santiago, *et al.* 1999, Meinhart, *et al.* 1999). It differs fundamentally from standard PIV in that it relies upon the sharp depth-of-focus of the microscopic objective to define the measurement volume in the dimension perpendicular to the viewing axis. Two distinct modes of operation are possible (Olsen and Adrian 2000, 2001). If the flow field is deep in the direction of the microscope's axis, the number of out-of-focus images must be controlled by reducing the concentration of particles. The out-of-focus images are manifested as a light background blur with the in-focus images being much more intense. The disadvantage to this approach is that one must perform correlation analysis of multiple frames of PIV images, and ensemble average them to build up a statistically stable correlations function from which to extract the mean particle displacement. This works if the flow is the same in each frame, i.e. steady or periodically sampled at constant phase.

The second mode, "high image density", relies on the depth of the flow field being small enough to limit the background glow of the out-of-focus particles by limiting their number. In this case, the concentration of particles is large enough to provide the 7-10 particles per interrogation volume that is needed to obtain statistically reliable correlations from a single frame. The PIV interrogation becomes virtually identical to conventional macroscopic PIV methods. Measurement volumes are typically  $10 \mu\text{m}$  cubes in this case, and therefore the micro-flow must be large enough for this sort of resolution to be adequate. Fortunately, there is a large class of flows that occur in channels of several hundred microns in size that are of practical interest. This paper focuses in flow fields of this type, and seeks to evaluate the accuracy of micro PIV measurements in such channels by comparing them with accurate CFD computations.

While steady, laminar flows of Newtonian fluids in simple geometries are not expected to present significant difficulties, either experimentally or computationally, it turns out to be surprisingly difficult to perform high quality experiments in micro-fluidic flows. In the experiments, the reasons are various, ranging from uncontrolled transients in the fluidic flows systems to fouling of the micro-channels by impurities, bubbles and the seed particles themselves. Thus, for example, even simple measurements such as pressure drop versus flow rate have, in the past produced erroneous friction factor data, and even lead some investigators to conclude that turbulent transition occurs prematurely in micro-channels (Mala and Li, 1999, Peng, *et al.*, 1994). Experiments to obtain correct friction factor data required much more care than expected (Sharp and Adrian, 2004), and measurements of flow fields are even more difficult.

Micro-flow measurements are also somewhat idiosyncratic to the type of fabrication used to construct the micro-channels. Various types of fabrication result in specific types of channel cross-section (trapezoidal for 011 etching in silicon, semi-circular for isotropic etching silicon and/or laser scribing in polymers, rectangular for machined and embossed channels.) One popular method for fabricating channels uses PDMS (polydimethylsiloxane). This channel material possesses a number of desirable properties such as transparency from the visible into the near ultraviolet; versatile surface chemistry; chemical inertness; and mechanical flexibility and durability. A rapid prototyping method based on photolithography is commonly used to fabricate PDMS micro-channels (Duffy, *et al.* 1999, Whitesides, *et al.*, 2001, Beebe, *et al.*, 2001).

We have developed a PDMS micro-channel test facility, Model 101-100P that contains a number of simple flow elements, Fig. 1, each molded 100  $\mu\text{m}$  deep into the PDMS and covered with an 80  $\mu\text{m}$  thick glass cover slip. The flow elements are:

Entrance flow into various channels (Fig. 2)

Channel 1:

- Fully developed flow in a 250 $\mu\text{m}$  wide channel
- Angled expansion at 45° from a 250 $\mu\text{m}$  wide channel to a 1000 $\mu\text{m}$  wide channel
- Flow around a square cylinder, 500 $\mu\text{m}$  x 500 $\mu\text{m}$  x 100 $\mu\text{m}$  tall (Fig. 3)
- Flow around a circular cylinder, 500 $\mu\text{m}$  diameter x 100 $\mu\text{m}$  tall
- Angled contraction at 45° from a 1000 $\mu\text{m}$  wide channel to a 250 $\mu\text{m}$  wide channel

Channel 2:

- Fully developed flow in a 150 $\mu\text{m}$  wide rectangular channel and a 750 $\mu\text{m}$  wide channel

Channel 3:

- An asymmetric contraction in which a 200 $\mu\text{m}$  wide inflow channel reduces abruptly to a 100 $\mu\text{m}$  wide outflow channel at a 71.565° angle
- A 'T' junction wherein two 100 $\mu\text{m}$  wide outflow channels branch at 90 degrees from a 100 $\mu\text{m}$  wide inflow channel
- Two 90 degree elbow turns in 100 $\mu\text{m}$  wide channels

Channel 4:

- An asymmetric 'T' junction wherein a 50 $\mu\text{m}$  wide outflow channel branches at 90 degrees to a 200 $\mu\text{m}$  deep inflow channel that narrows to a 150 wide outflow channel

In channels 3 and 4 the separation of the two parallel channel is 1500 micron (center to center). A reach of rectangular channel that is long enough to achieve fully developed flow at Reynolds numbers less than 100 precedes each flow element.

Construction of the Model 101-100P PDMS test facility is accomplished as follows. The mask for photolithography containing a negative image of the micro-channel device is created in a CAD program then printed on a transparency by a high-resolution printer. The mold is made from a silicon wafer coated by a 100 micron thick layer of photo resist (Nano XP SU-8 100, Microchem Corp., Newton, MA) by spin-coating at 2900 rpm for 30 s, followed by a soft-bake (95C for 30 min.), UV lithography (650 mJ/cm<sup>2</sup>), a post-bake (95C for 30 min), and development for 10 min. A pre-polymer of PDMS is then cast onto the mold and cured. The PDMS replica is then peeled from the silicon wafer leaving the channels cast into the surface of the cured PDMS.

To create closed channels a cover glass slip is bonded to the PDMS surface by oxidizing both the surface of the PDMS replica and glass by oxygen plasma treatment (70W, 85mTorr for 20s). When the two oxidized surfaces are brought into contact they bond covalently creating a seal, which can withstand up to 5 bars. The tightly sealed channels are necessary for pressure driven flow experiments to be conducted over a wide range of speed. Since the surfaces of the glass and the PDMS are each hydrophilic, filling the channels with aqueous liquids is relatively easy.

The Model 101-100P is intended as a test bed for micro-PIV techniques. To help validate the micro-PIV measurement we will perform high image density micro-PIV measurements and CFD computations of the flow in each of the flow elements. The CFD computations will use high-resolution grids and the Fluent software. The computations will assume fully developed inflow and outflow boundary conditions, justified by the long reaches upstream and downstream of the flow elements, (except possibly for the square and circular cylinders in the channel).

Measurements and computations will be compared in the presentation.

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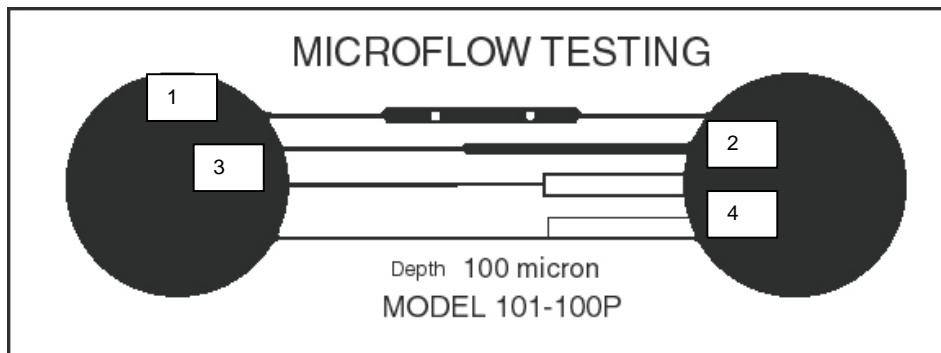


Figure 1. Model 101-100P micro-channel test facility fabricated in PDMS. The flow can be directed from either reservoir. All channels are 100 $\mu$ m deep with rectangular cross-sections.

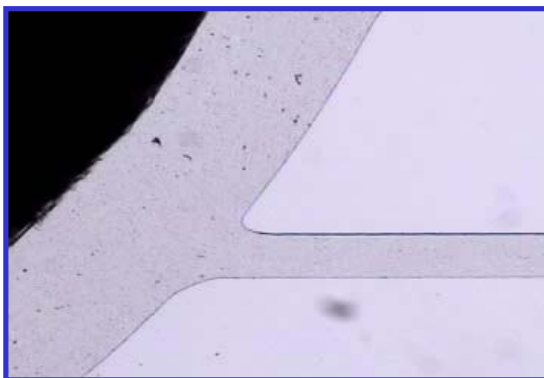


Figure 2. Entrance from the left reservoir to Channel 4.

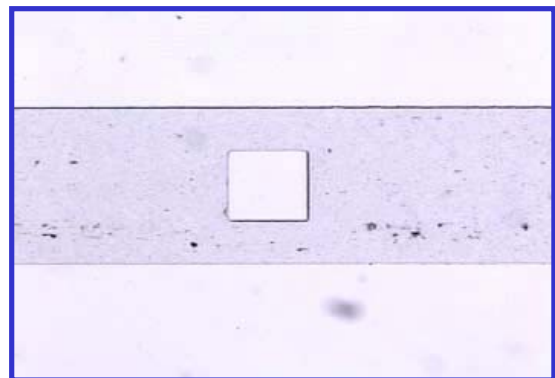


Figure 3. Square cylinder in the 1000  $\mu$ m wide section of Channel 1.