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Backward-Facing Step Flow in Microchannels Using Microparticle Image Velocimetry

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Flow at a backward-facing step feature (1:5 expansion ratio) in a microchannel has been studied using microparticle image velocimetry. The onset and development of a recirculation flow was studied as a function of flow rate. The onset of recirculation was initiated at flow rates that correspond to Reynolds numbers, $Re > 95$. The dimensions are such that recirculation flow has a three-dimensional structure and is expected to vary with the depth coordinate. Because of volume illumination, most microparticle-image-velocimetry measurements provide two-dimensional averaged flow profiles. Flow at the backward-facing step offers the opportunity to investigate the ability of resolving the depth dependency by conventional microparticle image velocimetry in relevance to two parameters: variation of the focus plane depth z^* and using variable time intervals for particle-image-velocimetry image pairs Δt. The ensemble cross-correlation algorithm was found to be insensitive to the variation of z^* for low magnification (4x) but was able to resolve the parabolic nature of flow across the depth of the channel, when high magnification objective lenses were used (20x). For a given flow rate and constant z^*, the variation of Δt resulted in quantitatively and qualitatively different flow patterns, suggesting that Δt is an indirect means of resolving the depth as the correlation algorithm locks onto a flow plane with particles moving at a speed that can be resolved with the given process parameters and time interval.

Nomenclature

A = channel cross-sectional area, μm^2
D_H = hydraulic diameter, μm; $4A/P$
H = channel height, μm
N = number of image pairs in particle-image-velocity correlation
P = channel perimeter, L/ min
Q = flow rate, μL/ min
Re = Reynolds number; $\rho U D_H/\mu$
w = channel width, μm
z^* = normalized focus plane depth; z/H
Δt = time interval between particle-image-velocity image pairs
Φ = correlation function

I. Introduction

MICROPARTICLE image velocimetry (μPIV) is a useful tool in studying small-scale flow and related phenomena in microfluidics. In comparison with conventional particle image velocimetry (PIV), the μPIV technique requires that the tracer particles be in the size range of the wavelength of the illumination light. The Brownian motion of tracing particles can be a source of error in low rates of flow. The illumination of the flow is not in a two-dimensional (2-D) plane, as in conventional PIV, but in an illumination volume. Hence, out-of-focus emissions from particles below and above the focus plane increase the noise-to-signal ratio. In addition to visualizing the onset and development of recirculation in microchannel flows, the purpose of this study is to investigate the effect of variables affecting μPIV in relevance to volume illumination: variation of the focus plane depth and time intervals between the PIV image pairs in a backward-facing step. An ensemble cross-correlation scheme was used to derive the flowfield.

In conventional PIV, the thickness of the illumination light sheet is much smaller than the characteristic dimensions of the flow, so that the flow can be analyzed layer by layer. In μPIV, however, all the particles in the flowfield are illuminated due to limited optical access; the intensity of light scattered by the tracer particles varies depending on their location from the plane of focus. The epifluorescence technique is implemented in μPIV, since the limited optical access does not allow illumination and collection of the excitation and reemission light from two separate paths. Fluorescent dyes offer the possibility of using only one optical pathway. Excitation light from a neodymium-doped yttrium aluminum garnet (ND:YAG) laser with a fixed wavelength is guided to the desired location of the flow; fluorescent dyes absorb this light, moving into an excitation mode. Upon releasing the absorbed energy, they reemit light at a higher wavelength (part of the energy gets dissipated). The reemission light can be filtered out using a dichroic mirror that is transparent to the wavelength used for excitation but reflective to the reemission wavelength. The reemission light is guided to the charge-coupled device (CCD) camera, where the images are recorded in pairs and eventually transmitted to a computer for further processing. The fact that all particles in the field of view are illuminated can be a major problem. The light from particles off the plane of focus forms a background noise (glow) that makes it difficult to distinguish between light scattered from in-focus particles and that from the off-focus particles. In most cases, information regarding the depthwise behavior of the flow is lost, and a 2-D average field is derived [1]. Two approaches are possible:

1) Choose the depth of field to be larger than the thickness of the flow. The depth can further be resolved by filtering techniques based on the intensity of light [2].

2) Choose the depth of focus to be significantly narrower than the depth of flow; in this sense, only a narrow slice of the flow would be in focus, and the light from seeding particles above or below the plane will be considered as noise [3].

Olsen and Adrian [4,5] introduced the concept of particle visibility for μPIV measurements while addressing this issue. Particles were considered to be visible if only their peak intensity in the recorded images rose significantly above the background glow. Particle visibility increases by decreasing the f number of the optical system; the depth of field increases by increasing the f number. This means that images taken with a low f number will tend to have a limited

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