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Infrared micro-particle image velocimetry measurements and predictions of flow distribution in a microchannel heat sink

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Abstract

The flow distribution in a silicon microchannel heat sink was studied using infrared micro-particle image velocimetry (IR μPIV). The microchannel test piece consisted of seventy-six 110 μm wide × 371 μm deep channels etched into a silicon substrate. Inlet and outlet manifolds, also etched into the substrate, were fed by 1.4 mm inner-diameter tubing ports. An image-processing algorithm was developed that significantly improves the quality of IR μPIV recordings in low signal-to-noise ratio environments. A general expression for the PIV measurement depth is presented, which is valid for PIV images that have undergone a threshold image-processing operation. Experiments were performed at two different flow rates: 10 ml/min ($Re = 10.2$) and 100 ml/min ($Re = 102$). Little flow maldistribution was observed at the lower flow rate. However, significant flow maldistribution was observed at $Re = 102$, with the channels near the centerline having an approximately 30% greater mass flux than the channels near the lateral edges of the heat sink. Numerical simulations carried out for flow in the microchannel heat sink agreed very well with the experimental measurements, validating the use of a computational approach for studying the effect of manifold design on flow distribution in microchannel heat sinks.

Keywords: Particle image velocimetry; Microchannels; Flow distribution; Maldistribution; Infrared; Optical diagnostics

1. Introduction

Microchannel heat sinks were first demonstrated by Tuckerman and Pease [1] as a high-performance cooling technique for microelectronics. The increase in cooling demands of high-performance microprocessors has generated increased interest in microchannel heats sinks over the past few years. Although the single-phase fluid flow and heat transfer characteristics in microchannels are now well understood [2,3], less attention has been devoted in the literature to flow distribution within the heat sink, which can adversely affect heat transfer performance. Numerical studies of flow maldistribution in minichannel and microchannel heat sinks have been performed [4,5]; well-characterized experimental results, however, have not been reported.

Accurate measurement of fluid flows in microchannel heat sinks requires diagnostic techniques with micron-scale spatial resolution. One such technique that has grown in popularity is micro-particle image velocimetry (μPIV). The technique was first demonstrated by Santiago et al. [6]. Measurements of the velocity field around a 30 μm elliptical cylinder were made in Hele–Shaw flow with a bulk velocity of approximately 50 μm/s. A spatial resolution of 6.9 × 6.9 × 1.5 μm was achieved. The technique was further demonstrated in a microchannel by Meinhart et al. [7], where a spatial resolution of 13.6 × 0.9 × 1.8 μm was achieved. The results agreed to within 2% of the analytical solution for laminar flow in a rectangular microchannel.

The use of μPIV has been limited to applications in which optical access to the fluid flow is available at visible wavelengths. In some applications such as stacked microchannel heat sinks, optical access to the fluid flow in the visible spectrum is unavailable. Since silicon is quite transparent to wavelengths between 1100 and 2500 nm, a

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Nomenclature

a	aperture radius
a_r	aspect ratio
d_e	effective particle diameter
d_p	particle diameter
d_s	diffraction-limited spot size
e	distance between pixels
F	optical fill factor
f	focal length
H_c	channel height
I_{max}	maximum intensity
I_{th}	threshold intensity
M	magnification
$\bar{m}''_c$	area-averaged mass flux in a channel
n	index of refraction
NA	numerical aperture
p	pressure
Re	Reynolds number based on hydraulic diameter of the channel
s	overall pixel dimension
u	velocity
u_{diff}	dimensionless diffraction variable
W_c	channel width
Greek symbols	
α	illumination angle
α_n	eigenvalue
δz_{diff}	contribution to δz_m due to diffraction
δz_{DOF}	depth of field
δz_{geom}	contribution to δz_m due to geometry
δz_m	PIV measurement depth
θ	half-angle subtended by extreme rays passing through microscope objective
λ	wavelength
λ_0	wavelength in a vacuum
μ	dynamic viscosity
ρ	density of fluid
ϕ	threshold intensity ratio

diagnostic technique in the infrared range would be advantageous for measuring subsurface flow fields in silicon microdevices. Han et al. [8] first demonstrated an infrared μPIV (IR μPIV) technique by measuring the velocity field in a micronozzle with a 300 μm depth and 40 μm throat width. The solid motion of a microrotor was also measured with this infrared diagnostic system. The IR μPIV technique was further discussed by Liu et al. [9], who obtained quantitative measurements in microtubes at various flow rates. The measurements were shown to agree well with laminar flow theory.

Although the IR μPIV technique has shown great promise, implementation of IR μPIV can be difficult due to a low signal-to-noise ratio. The two primary objectives of the present work are: (1) to present further developments to the IR μPIV technique, and (2) to study flow maldistribution in a silicon microchannel heat sink using this technique. The flow maldistribution is further explored using computational fluid dynamics modeling.

2. Experimental setup

2.1. IR μPIV system

The IR μPIV system layout is shown in Fig. 1. Infrared light from a wavelength-tunable, twin ND:YAG laser system is delivered to the micro-device through a fiber optic cable. A 20× magnification, 0.4 NA microscope objective, corrected for light in the 480–1800 nm range, collects the light scattered by the seed particles. A near-infrared (NIR) camera captures the particle images. The NIR camera employs a 320 × 256 pixel, indium–gallium arsenide focal plane array that is highly sensitive to wavelengths between 900 and 1700 nm. The pixel size is 30 × 30 μm with an optical fill factor greater than 90%. As discussed in Liu et al. [9], the choice of tracer particles is a compromise between flow traceability and particle visibility. A particle diameter of 2.0 μm was found to be adequate for the present study. The visibility of the particles is also greatly affected by the incident angle of the fiber optic delivery, α. The optimum incident angle is dependent on the light scattering characteristics of the tracer particles, which depend on the refractive index of the fluid and particle, the particle diameter, and illumination wavelength. Light scattering from the surfaces of the heat sink may also influence the optimum angle if the surfaces are not optically smooth. For the present work, α ≈ 30° was found to yield acceptable results.

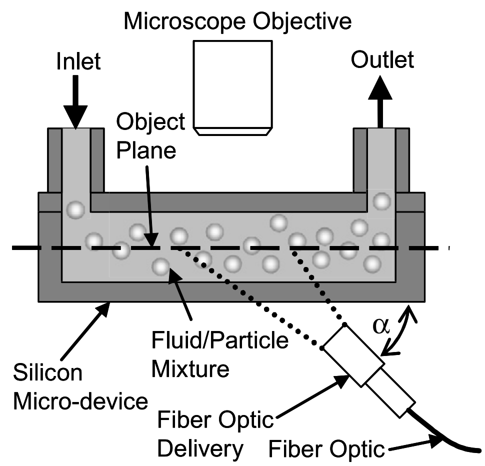

Fig. 1. IR μPIV system configuration.