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Convective heat transfer to shear-driven liquid film flow in a microchannel

Farzad Houshmand, Yoav Peles *

Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180, USA

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ABSTRACT

Experimental study on heat transfer to a liquid water film in a microchannel was performed. The liquid film was introduced into a nitrogen stream through a 350 μm circular hole upstream of a 1 mm × 1 mm heater in a 220 μm deep and 1.5 mm wide rectangular microchannel. Average heat transfer coefficient was obtained for different gas and liquid flow rates and results were compared to single-phase flow. Significant improvement in heat transfer performance was observed with no appreciable change in pressure drop. Experimental data combined with a heat transfer analysis was used to infer the mechanisms controlling the heat transfer process.

1. Introduction

Convective heat transfer in microchannels has long been a topic of much interest, and numerous studies have been published on the topic since the early work of Tuckerman and Pease [1]. Heat transfer characteristics of liquid and gas single-phase flow [2,3], jet impingement [4], pin fin heat sinks [5], and flow boiling of water [6,7], refrigerants [8], and coolants [9], have been extensively studied.

A heat transfer topic that has not been studied extensively at the micro scale is shear driven flow of thin liquid films. It refers to the flow of liquid film (on a heated surface) that is driven by a high velocity gas medium flowing alongside the liquid (Fig. 1). Conventional scale studies suggest that this type of flow is especially advantageous since it is accompanied by high heat transfer coefficients [10]; very few micro scale studies on the topic [11] suggest that it holds great potential for many miniature heat exchangers.

The hydrodynamics of liquid film flow has been studied extensively (e.g., [12–15]) over the years. Heat transfer from a vertical plate to a gravity-driven falling liquid film was experimentally investigated by Kabov and Chinnov [16]. Zeitsev et al. [10] studied the critical heat flux and film breakdown in gas-driven horizontal liquid film. Analytical and numerical modeling, as well as experimental study, in a mini-channel setup was performed by Kabov et al. [17] to investigate the flow of liquid film, film breakdown, and interface temperature. Kabov et al. [11] provided an overview of previous studies and compared critical heat flux results for shear-driven and gravity-driven water film flow. They also provided results for coolant FC-72 film flow and compared it with water.

Because shear driven flow at the micro scale is a promising cooling method, and since few studies have addressed this topic, an in-depth experimental investigation was conducted and is reported here. A 1 mm × 1 mm heater was fabricated inside a 220 μm deep and 1500 μm wide microchannel and the heat transfer coefficient for various gas and liquid flow rates was obtained. Flow visualization was performed to identify the hydrodynamics of the thin liquid film. The experimental data combined with a heat transfer analysis was used to infer the mechanisms controlling the heat transfer process.

2. Experimental setup and method

2.1. Micro fabrication

A 220 μm deep microchannel (Fig. 2) was fabricated using standard micro fabrication processes. The device consists of two processed Pyrex substrates attached together by an epoxy-covered vinyl layer. Nitrogen entered from an inlet manifold and flowed about 7 mm before reaching a 1 mm × 1 mm heater. Upstream of the heater, liquid water was injected through a 350 μm hole. Downstream of the heater, water and nitrogen continued to flow for an additional 7 mm in the channel before leaving through an exit manifold. A slot and several holes were cut on the vinyl layer

* Corresponding author. Tel.: +1 (518) 276 2886; fax: +1 (518) 276 2623.
E-mail addresses: farzad.houshmand@gmail.com (F. Houshmand), pelesy@rpi.edu (Y. Peles).

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Nomenclature

a	gas thickness (m)
A	heater area, (m^2)
A_c	cross-sectional area, (m^2)
A_i	interface area (m^2)
A_{liq}	heater area covered with liquid (m^2)
c_p	specific heat (J/kg K)
D_h	hydraulic diameter, (m)
D_{lg}	diffusion coefficient of the liquid to gas (m^2/s)
E_v	non-dimensional length for evaporation effects (–)
$\bar{h}$	average heat transfer coefficient, (W/m K)
$\bar{h}_m$	average mass transfer coefficient, (m/s)
h_{fg}	latent heat of vaporization (J/kg)
H	liquid film thickness (m)
j_i	superficial velocity of fluid i, (m/s)
k_l	liquid thermal conductivity, (W/m K)
k_{SiO_2}	SiO_2 thermal conductivity, (W/m K)
n''_{eV}	evaporative mass flux (kg/s m^2)
Nu	Nusselt number, (–)
P	pressure, (kPa)
q''_{eV}	evaporative heat flux (W/m^2)
$\dot{Q}_{loss}$	power loss, (W)
$\dot{Q}_{net}$	net power, (W)
$\dot{Q}_{tot}$	total power, (W)
Re	Reynolds number, (–)
$\bar{Sh}$	average Sherwood number, (–)
T_0	inlet temperature, (°C)
$\bar{T}_{heater}$	average heater temperature, (°C)
$\bar{T}_w$	average wall temperature, (°C)
u_f	interface velocity (m/s)
$\bar{V}$	average velocity, (m/s)
w_f	liquid film width (m)
Y	channel height (m)
α	thermal diffusivity (m^2/s)
Γ_i	volumetric flow rate of fluid i, (m^3/s)
δ_t	thermal boundary layer thickness (m)
ρ	density, (kg/m^3)
$\rho_{l,s}$	vapor density at the surface (kg/m^3)
$\rho_{l,\infty}$	vapor density in the gas stream (kg/m^3)
τ_i	shear stress of fluid i at the interface (N/m^2)

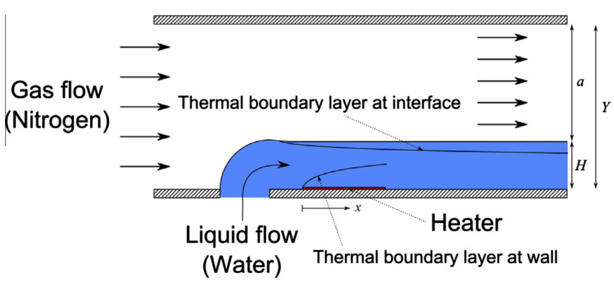

Fig. 1. Schematic cross-section of liquid film.

to form the channel and to provide access to the aluminum pads on the Pyrex. On the bottom Pyrex substrate, a 30 nm thick, 1 mm × 1 mm (1 mm × 0.94 mm due to over etching) titanium heater was deposited. A 1 μm thick aluminum layer on top of the titanium layer formed the electrical vias and contact pads. The titanium and the aluminum were deposited consecutively in a sputtering machine without breaking the vacuum. The extra material was subsequently etched away in sequence of lithography/chemical wet etching processes. A 600 nm SiO_2 film was then deposited on the heater and vias for electrical insulation (Fig. 3). A series of holes were also drilled in the same Pyrex substrate to form the flow inlets and outlet as well as the pressure ports. Similarly, holes were drilled in the top Pyrex substrate to allow electrical connection to the heater pads. Finally, individual devices on the attached substrates were separated from each other using a die-saw cutting machine.

The microdevice was seated in a package—built from Delrin using a CNC machine—that provided connection between fluidic

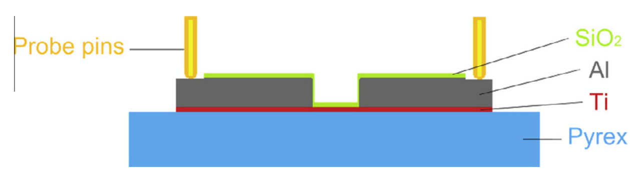

Fig. 3. Schematic cross-section of the deposited heater on the bottom Pyrex layer.

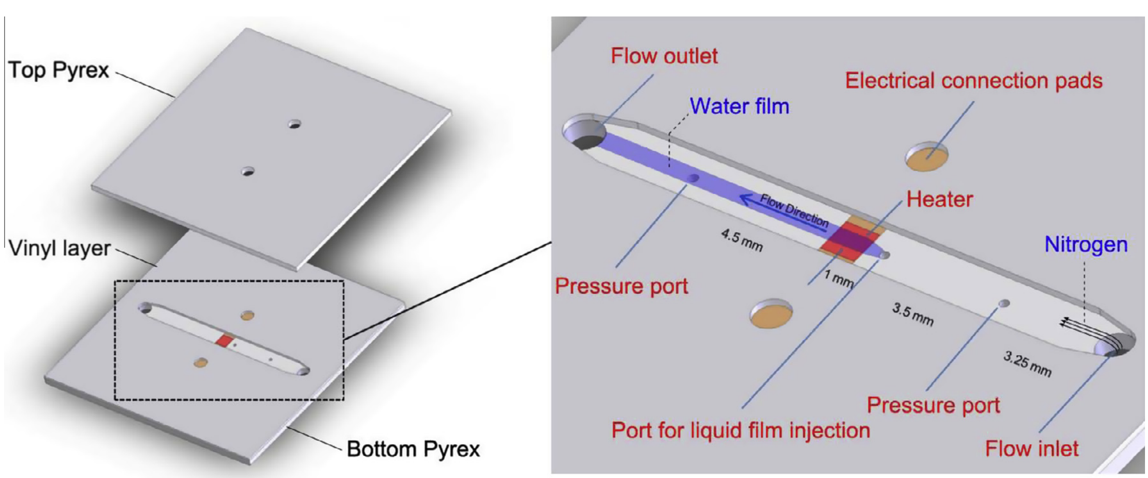

Fig. 2. Schematics of the microdevice.