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# Effect of taper on pressure recovery during flow boiling in open microchannels with manifold using homogeneous flow model

Ankit Kalani [a], Satish G. Kandlikar [a,b,*]

[a] *Microsystems Engineering, Rochester Institute of Technology, 168 Lomb Memorial Dr., Rochester, NY 14623, USA*
[b] *Mechanical Engineering, Rochester Institute of Technology, 76 Lomb Memorial Dr., Rochester, NY 14623, USA*

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## ABSTRACT

Flow boiling in microchannels is considered an attractive cooling option due to its small hydraulic diameter, latent heat effect and relative uniformity of coolant temperature. Although various techniques have been successfully employed to provide stable boiling operation in microchannels, it suffers from poor heat transfer performance with low critical heat flux (CHF) and low heat transfer coefficient (HTC). The tapered manifold with open microchannel (OMM) geometry provides stable operation with high heat transfer performance coupled with a very low pressure drop (less than 10 kPa). In this study, the pressure drop components from friction, acceleration and area changes during flow boiling of water at atmospheric pressure in the OMM geometry are evaluated using homogeneous flow model. Pressure recovery resulting from area change due to the taper is identified as a major factor in the extremely low pressure drops observed in this geometry. Seven viscosity averaging schemes are used to predict the frictional pressure drop. The best performing viscosity models are able to predict the pressure drop for the tapered configurations with a microchannel chip within an average MAE of less than ±30%. High speed visualization of the boiling phenomenon supports the applicability of the homogeneous flow model in the open microchannel geometry.

## 1. Introduction

Flow boiling at microscale has been identified as an efficient heat transfer process due to its ability to remove large amounts of latent heat and provide a reasonably uniform coolant temperature. Microchannels were introduced by Tuckerman and Pease [1] for single-phase cooling applications. In the past decade, they have been used for two-phase high heat flux conditions also. Microchannels provide a high surface area to volume ratio and a high heat transfer coefficient under operation. However, flow boiling in microchannels suffers from early CHF [2], flow instability [3] and low heat transfer performance [4]. Various techniques such as inlet restrictors [5], artificial nucleation sites [6], cross-linked channels [7,8] and reentrant cavities [9] have been employed in literature to provide stable operation. However, low heat transfer performance and excessive pressure drop remain a concern. Providing a variable (increasing) flow cross-sectional area along the flow length, a concept introduced by Mukherjee and Kandlikar [10,11], has garnered a lot of attention. Diverging channels [12,13], stepped microchannels [14,15] and expanding microchannels [16] have all been investigated with promising results. Kandlikar et al. [17] presented an open microchannel manifold concept which provided high heat dissipation of over 500 W/cm$^2$ (5 MW/m$^2$). Kalani and Kandlikar [18] investigated the effect of tapered manifold with open microchannel (OMM) and observed low pressure drops (below 10 kPa) at high heat fluxes.

The current work focuses on pressure drop modeling of the OMM geometry in an effort to understand the reasons for the dramatic reduction in pressure drop during flow boiling. Pressure drop modeling can be broadly classified into three approaches [19]: homogeneous flow model, separated flow model and flow regime based models.

The homogeneous model [20] is based on the assumption of equal liquid and vapor phase velocities. The model treats the two-phase flow as a pseudo single-phase flow with suitably phase-averaged viscosity and density equations. It is one of the most widely used models [21–27] that provides reasonable prediction of pressure drop over a wide range of parameters. The model has been used successfully for various fluids [28–31] including refrigerants, carbon dioxide, nitrogen gas and polyethylene glycol ether. It has shown a good predictive ability for both adiabatic

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* Corresponding author at: Mechanical Engineering, Rochester Institute of Technology, 76 Lomb Memorial Dr., Rochester, NY 14623, USA. Tel.: +1 585 475 6728; fax: +1 585 475 6879.

*E-mail addresses:* axk2161@rit.edu (A. Kalani), sgkeme@rit.edu (S.G. Kandlikar).

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## Nomenclature

| | |
|---|---|
| $G$ | mass flux, kg/s |
| $\dot{m}$ | mass flow rate, kg/m$^2$s |
| $A_c$ | cross-sectional area, m$^2$ |
| $A$ | projected area, m$^2$ |
| $f$ | fanning frictional factor |
| $u_m$ | average velocity, m/s |
| $L$ | length, m |
| $D$ | diameter, m |
| $D_h$ | hydraulic diameter |
| $Po$ | Poiseuille number |
| $Re$ | Reynolds number |
| $K_{ent}$ | entrance loss |
| $f_{app}$ | apparent fanning frictional factor |
| $L_{sp}$ | single phase length, m |
| $A_{ca}$ | channel area, m$^2$ |
| $A_p$ | total plenum cross-sectional area, m$^2$ |
| $Q$ | total heat transferred, W |
| $W$ | channel width, m |
| $C_p$ | specific heat |
| $L_{tp}$ | two-phase length, m |
| $f_{TP}$ | two-phase frictional factor |
| $v_f$ | specific volume of liquid, m$^3$/kg |
| $v_g$ | specific volume of gas, m$^3$/kg |
| $x$ | exit quality |
| $h_{fg}$ | latent heat of vaporization, kJ/kg |
| $q''$ | heat flux, W/m$^2$ |
| $\Delta P$ | pressure drop, kPa |
| $K_{exit}$ | exit loss |

*Greek symbols*

| | |
|---|---|
| $\alpha_C$ | channel aspect ratio |
| $\rho$ | density, kg/m$^3$ |
| $\Delta T_{Sub}$ | degree of subcooling, °C |
| $\frac{dx}{dz}$ | change of quality w.r.t channel length |
| $\frac{dA}{dz}$ | change of c/s area w.r.t channel length |
| $\mu_l$ | liquid viscosity, Pa-s |
| $\mu_v$ | vapor viscosity, Pa-s |
| $\frac{dp}{dz}$ | pressure drop, kPa |

*Subscript*

| | |
|---|---|
| *c* | channel |
| *m* | mean |
| *l* | liquid |
| *v* | vapor |
| *sub* | subcooled |
| *sp* | single phase |
| *tp* | two-phase |
| *exp* | experimental |
| *g* | gas |
| *app* | apparent |

and diabatic conditions, especially in the bubbly, churn and wispy annular regimes, where uniform phase velocities is a reasonable approximation.

Bowers and Mudawar [32] used the homogeneous model for their microchannel and minichannel heat sink geometries. The model predicted well for their R-113 experimental data within ±30% error band. In a later publication [33], the authors added the effects of flashing and compressibility to the homogeneous model. Field and Hrnjak [28] used four different refrigerants in their adiabatic pressure drop study for a rectangular channel with a hydraulic diameter of 148 µm. They compared their experimental data with the homogeneous model and separated flow model. The authors developed a new Chisholm parameter C used in the separated flow model. Saisorn and Wongwises [34] investigated the applicability of various viscosity correlations in their air–water experiments. McAdams et al. [24] and Beattie and Whalley [26] showed good agreement between their models and their own experimental data. Lee and Mudawar [35] investigated the pressure drop model for their microchannel heat sink arrangement at various mass flux and heat flux conditions with R134a and noted that the homogeneous model underpredicted their data. They developed a new correlation using the separated flow model which gave a mean deviation of less than 10%.

Choi and Kim [36] used water and nitrogen gas in a single microchannel for their adiabatic two-phase pressure drop study. They investigated the homogeneous model with seven different viscosity averaging schemes and the separated flow model with ten different correlations. For the homogeneous model, Beattie and Whalley's [26] viscosity equation showed the best prediction with a minimum deviation of ±50%. The authors also proposed a new correlation. The homogeneous model has also been used in the application of condensation in a vertical tube. Dalkilic et al. [37] used ten different viscosity correlations in their study and found that Owens [21], Lin et al. [23] and McAdams et al. [24] models showed the least deviation with experimental data within ±30%.

In the current work, the homogeneous model with seven viscosity averaging schemes is used to predict the frictional pressure drop data for the OMM geometry. The acceleration and area change terms are obtained from the equations presented by Collier [20]. Experimental data with water from uniform and tapered manifold configurations with two copper chips (plain and microchannel) were obtained and compared with the homogeneous model predictions. A comparison among various taper gradients is also discussed with different viscosity models. Various components (friction, acceleration and area change) of the homogeneous model are discussed individually through pressure drop and heat flux plots. Lastly, images from a high speed camera are shown for plain

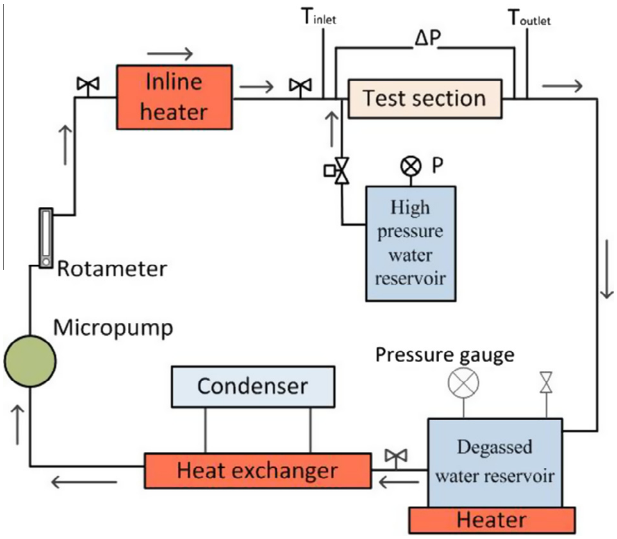

**Fig. 1.** Schematic of the flow boiling test loop.