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Volume of fluid-based numerical modeling of condensation heat transfer and fluid flow characteristics in microchannels

H. Ganapathy [a], A. Shooshtari [a], K. Choo [a], S. Dessiatoun [a], M. Alshehhi [b], M. Ohadi [a,*]

[a] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA
[b] Department of Mechanical Engineering, The Petroleum Institute, P.O. Box 2533, Abu Dhabi, United Arab Emirates

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ABSTRACT

The present work proposes a numerical model for the simulation of condensation heat transfer and fluid flow characteristics in a single microchannel. The model was based on the volume of fluid approach, which governed the hydrodynamics of the two-phase flow. The condensation characteristics were governed by the physics of the phenomena and did not include any empirical expressions in the formulation. The conventional governing equations for conservation of volume fraction and energy were modified to include source terms that accounted for the mass transfer at the liquid–vapor interface and the associated release of latent heat, respectively. A microchannel having characteristic dimension of 100 μm was modeled using a two-dimensional computational domain. The working fluid was R134a and the vapor mass flux at the channel inlet ranged from 245 to 615 kg/m^2 s. The channel wall was maintained at a constant heat flux ranging from 200 to 800 kW/m^2. The predictive accuracy of the numerical model was assessed by comparing the two-phase frictional pressure drop and Nusselt number with available empirical correlations in the literature. A reasonably good agreement was obtained for both parameters with a mean absolute error of 8.1% for two-phase frictional pressure drop against a recent universal predictive approach, and 16.6% for Nusselt number against an available correlation. Further, a qualitative comparison of various flow patterns against experimental visualization data also indicated a favorable agreement.

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1. Introduction

Miniaturization of electronic devices has led to advances in various engineering fields, including space technology, defense systems, aerospace applications, manufacturing technology, industrial processes and consumer electronics. Researchers in these fields are investigating ways to manage the thermal dissipation from electronic components in miniaturized devices, with the aim of guaranteeing the reliability and safety of the device during operation. The use of microscale heat exchangers to manage this thermal dissipation has been widely studied since the pioneering work of Tuckerman and Pease [1]. Since then, majority of the literature has focused on characterizing the heat transfer coefficient and pressure drop for electronics cooling applications, as reported by Sobhan and Garimella [2]. While changes in simple channel geometries can yield significant enhancements in thermal performance, the improvements come at the expense of high pressure drops. However, this drawback is being actively mitigated by the development of advanced designs for microchannel heat exchangers, using innovative fluid feed systems (Ohadi et al. [3], Kim et al. [4]).

A major advantage of numerical modeling of heat transfer over simpler empirical correlation-based approaches is that, the former, when appropriately validated with experimental data, may serve as an effective tool for the design and optimization of next-generation, compact heat exchangers utilizing complex geometries. While correlations are specific to the geometries for which they were originally developed, numerical modeling, once validated, can be extended to non-conventional and more complicated geometries. Additionally, numerical modeling provides insight into the details of the flow field and transport phenomena. The present work focuses on the development of a purely theoretical, validated approach for modeling condensation heat transfer and the associated fluid flow characteristics in microchannels. For the purposes of this paper, we follow the widely accepted classification terminology of Kandlikar and Grande [5] which defines minichannels as channels having characteristic dimensions between 200 μm and 3 mm, and microchannels as those between 10 and 200 μm.

Existing approaches for modeling phase change phenomena under steady state conditions include the formulation proposed by

* Corresponding author. Address: Center for Environmental Energy Engineering (CEEE), 4164C Glenn L. Martin Hall, Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA. Tel.: +1 301 405 5263; fax: +1 301 405 2025.

E-mail address: ohadi@umd.edu (M. Ohadi).

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Nomenclature

Bo	Bond number (–)
C	Courant number (–)
Ca	capillary number (–)
D	characteristic dimension (m)
E	energy per unit mass (J/kg)
f	friction factor (–)
F	force (N)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{LV}	latent heat (J/kg)
k	thermal conductivity (W/m K)
MAE	mean absolute error (%)
N	number of data points for calculating average
n_{phase}	number of phases
Nu	Nusselt number (–)
P	pressure (Pa)
q''	heat flux (W/m^2)
S_h	energy source term (kg/m s^3)
S_α	mass source term (kg/m^3 s)
t	time (s)
T	temperature (K)
V	velocity (m/s)
x	vapor quality (–)
X	Martinelli parameter (–)
Y	vertical axis in Cartesian coordinates
Z	horizontal axis in Cartesian coordinates

Greek symbols

α	volume/void fraction (–)
δ	thickness of thin liquid film (m)
ϕ	two-phase multiplier (–)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts and superscripts

A	acceleration
eff	effective
F	friction
i	denotes the ith phase
L	liquid
LO	liquid only
sat	saturation
TP	two-phase
V	vapor
VO	vapor only
$wall$	channel wall

Wang and Rose [6–8], wherein they reported a fundamental approach for laminar film condensation based on the Nusselt approximations, which was subsequently applied to study different minichannel geometries. Similarly, Wu et al. [9] reported a three-dimensional model for steady state annular condensation in rectangular microchannels.

While boiling heat transfer involves numerous, complex physical mechanisms, the physics governing evaporation, in addition to being simpler, also closely resembles that responsible for condensation heat transfer. From a modeling perspective, both these modes bear certain resemblances to the presently studied condensation heat transfer, and are therefore reviewed here. Heat transfer from thin films during evaporation comprises a meniscus region, an evaporating thin film region, and a nanoscale non-evaporating region. Wang et al. [10,11] utilized a Young–Laplace approach coupled with kinetic theory-based expressions for modeling thin film evaporation in microchannels. Subsequently, Mandel et al. [12] coupled the models of Wang et al. [8] and Xu and Carey [13] to obtain an improved formulation of the problem and therefore better accuracy. Modeling of similar problems using kinetic theory-based expressions in conjunction with commercial CFD codes was reported by Ranjan et al. [14] for thin film evaporation in capillary wicks and by Wang et al. [15] for an evaporating meniscus in an open V-microgroove.

All of the above studies were based on steady-state analysis. In other words, a solution of the governing equations yielded the profile of the liquid–vapor interface, based on which, the two-phase heat transfer performance was estimated. An alternative approach is to continuously track the transient liquid–vapor interface. This results in a highly accurate prediction of the interfacial area in the microchannel, which in turn influences the phase change mass flux and heat transfer. The method generally involves including mass and energy source terms in the multiphase flow model, and implementations of the same for film boiling problems have been reported by several groups. Juric and Tryggvason [16], Esmaeeli and Tryggvason [17,18], and Tryggvason et al. [19] implemented the front tracking model of Unverdi and Tryggvason [20], Son and Dhir [21] implemented the level set method of Sussman et al. [22], and Welch and Wilson [23] implemented the volume of fluid (VOF) method of Hirt and Nichols [24].

Zhang et al. [25] modeled condensation in a minichannel using the VOF model to govern the interface, and defined mass and energy source terms to model the phase change phenomena. A steady-state solution was obtained for the transient problem using a false transient method. The model was validated based on the liquid film thickness during Nusselt condensation on a vertical flat plate.

Mukherjee and Kandlikar [26] modeled the growth of a single bubble due to evaporation during flow boiling in a microchannel. This was a fundamental study that applied Fourier's law to estimate the heat flux at the liquid–vapor interface and determine the corresponding evaporation mass flux based on the latent heat. The level set method was implemented to govern the liquid–vapor interface. The results demonstrated the axial growth of a single bubble as it progressed through the channel and the same was qualitatively validated against the available experimental visualization data of Balasubramanian and Kandlikar [27].

Wu et al. [28] and Yang et al. [29] modeled flow boiling in conventional channels having a serpentine structure using the Eulerian and the VOF models, respectively. The phase change was modeled following the approach of Lee [30] which assumed a quasi-thermo equilibrium state at constant pressure, with the mass transfer being determined by the saturation temperature. Empirical coefficients were present in the expressions for the source terms and appropriate values for the same were recommended in order to maintain the interfacial temperature reasonably close to the saturation temperature, and to avoid divergence issues. The phase distribution in the channel was qualitatively compared with experimental visualization data.

Fang et al. [31] modeled flow boiling in a vapor–venting microchannel. The system was designed to locally vent the generated vapor phase into a separate secondary channel, thereby ensuring that the primary channel is predominantly occupied by the liquid phase. The interface was governed by the VOF model and their mass transfer formulation was similar to that of Yang et al. [29]. The effect of the porous membrane that performed the venting ac-

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