International Journal of Thermal Sciences 89 (2015) 87–99

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Numerical modeling of annular flow with phase change in a microchannel

S. Jesseela [a, *], C.B. Sobhan [a, b]

[a] Department of Mechanical Engineering, National Institute of Technology, Calicut 673 601, India
[b] School of Nano Science and Technology, National Institute of Technology, Calicut 673 601, India

ARTICLE INFO

Article history:
Received 3 May 2014
Received in revised form
27 October 2014
Accepted 27 October 2014
Available online

Keywords:
Microchannels
Annular flow
Quasi-3D analysis
Pressure drop
Slip flow
Heat transfer coefficient

ABSTRACT

Phase change phenomena in microchannels have been projected as an effective option for thermal management of various microscale systems. However, for the design of heat sinks which utilize these phenomena, a clear understanding of the physical mechanisms involved, in the microscale domain, is required. In the present study, a numerical simulation is carried out to predict the characteristics of two phase flow with liquid to vapor phase change, in rectangular microchannels for a range of hydraulic diameters. The annular flow pattern, reported to be the most common in microchannel, has been investigated, with water as the flowing medium. The analysis considers, among other parameters, the effect of surface tension on the flow dynamics, which could be significant in microchannels. The mathematical model is numerically solved using a quasi-three dimensional approach, incorporating the variations in the cross-sectional areas of both the phases along the flow direction. Since it is expected that the continuum approximation may be insufficient in the vapor domain in channels of very small dimensions, an analysis incorporating slip flow at the liquid vapor interface analysis has been performed, where the channel dimensions produce Knudsen number values in the range 0.001–0.1, as suggested in the literature. The liquid film thickness along the flow direction is determined utilizing mass conservation, and the velocity distributions at different locations along the flow direction are obtained by solving the governing differential equations numerically. The two phase pressure drop is calculated for cases demanding slip and no slip conditions. A comparison has been made of the fluid flow characteristics, between the slip and no slip cases for the cases where slip flow is expected. The effects of the imposed heat flux, volume flow rate and channel geometry on the velocity distribution and pressure drop are examined. The predicted pressure drop values are found to increase with increasing heat flux, and decrease with an increase in the flow rate and the channel height. The two phase heat transfer coefficient and the wall temperature of the channel are also determined. The two phase heat transfer coefficient is found to increase with an increase in the vapor quality. It is also noticed that the wall temperature decreases along the length of the channel and the wall temperature at the exit of the channel decreases with decrease in volume flow rate, within the range of parameters used, which is in accordance with observations reported in the literature. The results are found to be in good agreement with the experimental and theoretical results available in the literature.

1. Introduction

Due to the advances in miniaturization and the ever increasing processing speeds, the present day technology demands a large amount of heat to be dissipated from limited surface areas of microscale systems and devices. Microchannel heat sinks have emerged as a promising option, which have remarkable heat removal capabilities, because of their large surface area to volume ratios. Phase change phenomenon in microchannels has been envisaged as an effective method for heat dissipation, as this would offer a large heat removal capability, as well as uniformity of surface temperatures. However, for effective thermal design and operation of heat sinks utilizing phase change, a thorough understanding of the characteristics of the two-phase fluid flow in the microscale

* Corresponding author.
E-mail address: jessyhamza@gmail.com (S. Jesseela).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.10.017
1290-0729/

Nomenclature

A	area of cross section, m^2
c_p	specific heat, J/kg °C
D_h	hydraulic diameter, m
G	mass flux, kg/m^2 s
h	heat transfer coefficient, W/m^{2}K
H_c	channel height, m
h_{lv}	latent heat of evaporation, J/kg
L	length of the channel, m
$\dot{m}$	mass flow rate, kg/s
$\dot{m}_{in}$	mass flow rate at inlet, kg/s
n	positive direction vector.
P	pressure, bar or kPa
q	heat flux,W/cm^2
Q	volume flow rate, ml/min
r	meniscus radius, m
Re	Reynolds number
T	temperature, K
u	axial velocity, m/s
U	dimensionless axial velocity
$\bar{u}$	mean axial velocity, m/s
$\bar{U}$	mean dimensionless velocity
v	velocity component in y direction, m/s
w	velocity component in z direction, m/s
W_c	width of the channel, μm
x	distance from zero thermodynamic quality to any x location, m
x_d	vapor quality
Y	dimensionless distance in the y direction
Z	dimensionless distance in the z direction
α	void fraction
β	aspect ratio, H_c/W_c
δ	liquid film thickness, μm
λ	molecular mean free path, nm
μ	dynamic viscosity, N-s/m^2
ρ	density, kg/m^3
σ	surface tension N/m
τ	shear stress, N/m^2

Subscripts

c	channel
dev	developing
fd	fully developed
in	inlet
l	liquid
v	vapor
0	zero thermodynamic quality
sat	saturated
sp	single phase
tp	two phase
w	wall
x	location x

domain is required. As an optimal design of microchannels with phase change needs restriction and control of the pressure drop encountered in the flow, fluid dynamic analysis and pressure drop estimation in such systems becomes an important problem.

Several investigations have been reported in the area of phase change and two phase flow in microchannels, as reviewed by Sobhan and Garimella [1], Thome [2] Bertsch et al. [3], Tibirica and Ribatski [4] and Szczukiewicz et al. [5]. Qu and Mudawar [6] measured the two phase pressure drop in a water-cooled microchannel heat sink and developed a correlation based on the results. In addition, they also examined the predictive capability of different correlations available in the literature. Lee and Garimella [7] experimentally investigated the flow-boiling of water in a microchannel array. Based on their observations, they suggested the dominance of convective boiling at high heat fluxes and reported an increase in pressure drop with the heat flux. They also suggested a correlation, which predicted the two-phase pressure drop better than the existing correlations. Singh et al. [8] investigated the effect of aspect ratio of microchannels on the two phase pressure drop, experimentally and also using a theoretical model. Their findings suggested the existence of an aspect ratio that gives the minimum pressure drop.

Most of the studies reported on two phase flow in compact passages and microchannels have been experimental in nature, or analyses based on experimental correlations. However, a flow-pattern based model would give a more realistic description of the transport in the two phase region, and also would be applicable to a wide range of parameters than an analysis based on empirical correlations [9,10]. Hence, such an analysis has been attempted in the present work.

On the basis of a critical review of the literature and also based on the work of his group, Kandlikar [11] identified the occurrence of three flow patterns namely isolated bubble, confined bubble or plug/slug and annular flow during flow boiling in minichannels and microchannels. Based on the heat transfer model developed, Thome [2] concluded that the most dominant flow regime in the microchannel is the elongated bubble followed by annular flow. Zhang et al. [12] conducted experiments on microchannels with hydraulic diameters ranging from 25 μm to 60 μm. Based on optical microscopic measurements, they reported that annular flow is the most expected flow pattern in microchannels, and that bubbly and plug flow patterns were not observed in their experiments. Qu and Mudawar [13] conducted experimental studies on microchannels with water as the working fluid and identified the existence of annular flow regime near the point of zero thermodynamic equilibrium quality, and also noticed a decreasing heat transfer coefficient with an increasing quality. Thome et al. [14] observed that evaporation of thin liquid film surrounding the elongated bubble is the dominant heat transfer mechanism in microchannels, opposed to nucleate boiling. Harirchian and Garimella [15] conducted experiments on microchannels using Fluorinert FC-77 as the cooling fluid, to investigate the effect of channel size and mass flux on the flow boiling regimes. They reported the dominance of nucleation boiling in channels of width ranging from 400 to 5850 μm. They found that the flow regimes in channels of width below 400 μm are different from large passages. They also suggested that the bubble nucleation at the wall can be suppressed and transition to annular flow can happen at relatively low heat fluxes. Cheng et al. [16] noticed that the nucleation mechanism usually dominates near the point of onset of boiling at the upstream of the microchannels while film vaporization becomes predominant in annular flow at the downstream.

The findings in the literature suggest annular flow to be the best suited model for fluid flow with phase change in microchannels. Qu and Mudawar [9] have developed an analytical annular flow model to predict the two phase pressure drop in a rectangular microchannel. They considered the droplet entrainment and deposition effects and used an assumption of uniform annular liquid film