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Joule heating in low-voltage electroosmotic with electrolyte containing nano-bubble mixtures through microchannel rectangular orifice

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ABSTRACT

Joule heating effects on a rectangular orifice in microchannel filled with electrolyte containing nanobubbles are comprehensively investigated with emphasis on the thermal boundary conditions. Numerical studies are performed for the velocity and temperature fields to show the various aspects of fluid flow and thermal design in rectangular shaped microchannels. Furthermore the correlations for the maximum temperature increase were presented for several geometry parameters and thermal boundary conditions which gives us an insight to the best cooling scenario of microfluidic rectangular orifices. This study will provide useful information for the optimization of a bioMEMS device in thermal aspect and benefits of nano-bubble injection for temperature control. It is shown that the cooling from the side is superior in reducing the peak temperature of the micro-orifice.

1. Introduction

The Joule heating in bio-microfluidic systems with high electric conductivity has been attracting many interests because of the considerable temperature increment of the system (Horiuchi and Dutta, 2004; Xuan, 2008; Chaurey et al., 2013; Gao et al., 2011; Desai and Voldman, 2011; Braun and Libchaber, 2002). The Joule heating problem appears in many applications of magnetohydrodynamic flow (Shahidian et al., 2009; Jamalabadi et al., 2015; Jamalabadi, 2014). There are many experimental studies to investigate the various thermal characteristics of Joule heating phenomena in microfludic systems (Erickson et al., 2008; Tang et al., 2006) Also this phenomena can be used to control the temperature (de Mello et al., 2004; Ross et al., 2001; Johnson et al., 2002; Tang et al., 2007; Xuan et al., 2004), dielectrophoretic trapping (Chaurey et al., 2013; Burg et al., 2010), generating the dielectrophoresis forces (Castellanos et al., 2003), creating the fluid inhomogeneities (Sridharan et al., 2011), bio-particles manipulation in aqueous media (Pethig, 2013), and electrokinetic transport (Cetin and Li, 2008).

The stokes flow problem through orifices has been considered before and the analytic results of the Dagan et al. (1982) is one of the first works on it. Recently Mishra and Peles (2005a,b) studied hydrodynamic cavitation flow through orifices in rectangular micro-channels experimentally. For obtaining hydrodynamic cavitation they applied a great value of mass flow which is beyond those typical of bio-MEMS

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Nomenclature

a	interfacial area per volume, =1/m
A	micro-channel aspect ratio, $=\frac{h}{W}$
C_p	heat capacity, J/(kg K)
$\mathbf{E}$	electric field, V/m
$\bar{\mathbf{E}}$	dimensionless electric field $=\frac{EH}{\varphi_{max}-\varphi_{min}}$
H	channel height or system thickness, m
l	orifice length, m
L	system length, m
M	molecular weight of the air gas, =29 kg/mol
n	number density of the air gas, $1/m^3$
k	thermal conductivity, W/m K
p	pressure, Pa
Pe	Pclet number $=\frac{U_{in}W}{\alpha}$
R	ideal gas constant, 8.314472 J/(mol K)
Re	Reynolds number $=\frac{U_{in}W}{\nu}$
t	time, s
T	temperature, K
x, y	Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinate = x/H, y/H
$\vec{u}$	velocity vector, m/s
w	the orifice width, m
W	the micro-channel width, m

Greek symbols

α	thermal diffusivity $=\frac{k}{\rho C_p}$, m^2/s
λ	orifice length-to-width ratio$=\frac{l}{w}$
γ	orifice contraction ratio $=\frac{w}{W}$
μ	dynamic viscosity of the liquid, Pa
ρ	fluid density, kg/m^3
ϕ	phase volume fraction
φ	electric potential, V
Φ	dimensionless electric potential $=\frac{\varphi-\varphi_{min}}{\varphi_{max}-\varphi_{min}}$
σ	electric conductivity, S/m
θ	dimensionless temperature $=\frac{k(T-T_\infty)}{\sigma(\varphi_{max}-\varphi_{min})^2}$
τ	dimensionless time $=\frac{\alpha t}{H^2}$

Superscripts

d	drift
f	fluid
g	gas
gl	mass transfer rate from gas to liquid, $kg/(m^3\,s)$
max	maximum
min	minimum
∞	ambient
ref	reference pressure, 101325 Pa
s	slip
sat	saturation

devices. Zivkovic et al. (2013) studied flows through a rectangular orifice in low Reynolds number numerically and obtain a correlation pressure drop. They have not considered the Joule heating through the system. The flow (Ushida et al., 2014) heat (Zhang and Li, 2013), and mass transfer (Mei et al., 2014) of through micro devices in a range of low Reynolds numbers are studied in the literature without considering the Joule heating effects. Drag reduction effect of nanobubble mixture flows through micro-orifices are studied in Ushida et al. (2012, 2012). Also the effect of Zeta potential (Kim et al., 2000; Cho et al., 2005), pH (Jin et al., 2007), and capillary forces (Hampton and Nguyen, 2010) are investigated experimentally and the use of Lattice Boltzmann simulations (Harting et al., 2010) for the modelling of the nanobubble in microchannels are found in the literature.

In addition, the need of optimal thermal design in micro scales leads to the question of finding the best preparation capable of self passive cooling at these scales. By this, researchers mean the ability to cooling by performing the heat transfer processes at the best positions. Recent cooling means and optimal designs in cooling systems, involve in optimal designs problems in conductive cooling systems (Hajmohammadi et al., 2013, 2014, 2014, 2013, 2014; Pouzesh et al., 2015), convective cooling systems (Shokouhmand and Salimpour, 2007; Hajmohammadi et al., 2013, 2013, 2013, 2006, 2015; Najafi et al., 2011) and radiative cooling systems (Hajmohammadi et al., 2012; Jamalabadi et al., 2012, 2013, 2015; Jamalabadi, 2014).

The common problem in conductive cooling systems is the shape optimization as maintaining the peak temperature of a heat source under an allowable level has always been a major concern for engineers engaged in the design of cooling systems for electronic equipment. For example Hajmohammadi et al. (2014) investigated the various shape to insert conductive routes for improved cooling in a heat generating piece (like electronic chips) and find that which shape is superior in minimizing the maximum temperature, which must not exceed a preset value. Furthermore Pouzesh et al. (2015) find that the triangular and Y-shaped cavities are reliable options among the different shapes studied in their work. The optimization can also contain the various aspect such as energy and cost which cause to solve a multi-objective optimization problem. The common problem in convective and radiative cooling systems is the finding the best Reynolds number (Shokouhmand and Salimpour, 2007), or optimal placement of the insulated segments (Hajmohammadi et al., 2013) or the heated segments (Hajmohammadi et al., 2013) is calculated according to constructal design as done by Hajmohammadi et al. in the array of heated segments. Such systems need to control the excess (peak) temperature of a thick plate which is placed between the heat sources with an isoheat flux and the cooling fluid which cooled the plate by laminar forced convection flow (Hajmohammadi et al., 2014). The natural trend of fluid flow with the best possible conformation means in what manner to optimally deal out faultiness during the course of the fluid flow, so that it moves best with the minimal loss and minimal degeneracy, i.e. it moves within the smallest amount costly way. This is the vital concept of constructal theory that states that “for a finite-size system to persevere in time, it must change in such a way that make available easier right to use to the carried out currents flowing throughit”. Using Constructal theory, this natural behavior can be considered as a spectacle of configuration generation. Constructal theory has been planned, because of its applicability to natural and engineering flow systems, and a lot of work has been done based on this theory (Pouzesh et al., 2015). Other than constructal design (Hajmohammadi et al., 2013, 2012), the entropy minimization method (Hajmohammadi et al., 2006; Jamalabadi et al., 2015) is an effective tool which suggest the best exergy utilization with the least irreversibility in thermal systems.

Nonetheless, previous researches have not provided detailed information about the various boundary condition effects on the Joule heating in rectangular orifices in microchannels and the effect of nano-bubble injection on thermal design of them. The results of the current study include the detailed thermal characteristics such as fluid