International Journal of Heat and Mass Transfer 70 (2014) 827–834

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Three-dimensional vortex structures on heated micro-lattice in a gas

Steffen Jebauer, Justyna Czerwinska *

Artorg Center for Biomedical Engineering, Bern University, Murtenstrasse 50, CH-3010 Bern, Switzerland

A R T I C L E   I N F O

Article history:
Received 14 May 2013
Received in revised form 18 November 2013
Accepted 18 November 2013
Available online 18 December 2013

Keywords:
Gas flow
Simulations
Secondary slip induced flow structures
Heated micro-lattice

A B S T R A C T

This paper addresses the microscale heat transfer problem from heated lattice to the gas. A micro-device for enhanced heat transfer is presented and numerically investigated. Thermal creep induces 3-D vortex structures in the vicinity of the lattice. The gas flow is in the slip flow regime (Knudsen number $\mathrm{Kn} \leqslant 0.1$). The simulations are performed using slip flow Navier–Stokes equations with boundary condition formulations proposed by Maxwell and Smoluchowski. In this study the wire thicknesses and distances of the heated lattice are varied. The surface geometrical properties alter significantly heat flux through the surface.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In recent years micro-electro-mechanical systems (MEMS) have become important devices for numerous purposes. These devices with sizes in the micro-metre-range involve sensors of all kinds, systems for DNA treatment and detection, drug delivery systems and various types of valves, pumps or turbines. Their complex structure combines mechanical elements with electronic circuits, with the purpose to transport mass, momentum and energy. In the field of microfluidics MEMS allow to carry out analyses with high resolution and sensitivity as well as other merits [28] at smallest fluid amounts. Many MEMS are fabricated from silicon wafers using processes such as photolithography for mask production, etching, doping or bonding with additional wafer layers. This whole set of techniques matured due to extensive use in the electronic chip production industry e.g. for central processing units (CPU). Similar to CPUs Joule heating from electric currents makes heat removal a crucial issue to be considered to avoid device failure or damage. This is especially true when device sizes are minimised and the level of integration and package density is increased [5]. Basically, of the three modes of heat transfer conduction and convection are most commonly used in micro-devices. Conductive heat removal is performed using thermoelectric coolers, microrefrigerators or thin-film refrigerators [32]. Other examples are presented in [4,12,29,31].

Heat removal by forced convection is another approach where various fluids can be utilised. Extensive reviews on heat transfer in micro-size devices where liquids or gases are propelled through and around devices in experimental as well as in numerical observations are available e.g. in [8,15,20,33]. Oscillation in Nusselt number depending on the channel structures was reported in [21], where flow in wavy channel was considerate. The thermal creep can be introduced by the geometry curvature or the temperature distribution. The periodic geometry changes introduce similar slip behaviour as the one by presented below heated lattice. Micro heat sink which uses water and flow induced separation structures was presented in paper [18]. Flows at this size range behave different than those at the macro-scale and in general observations from macroscopic systems cannot be transferred to microscopic flows [11]. For example, viscous effects dominate the flow over inertia effects, thus turbulence or natural convection are absent or play a minor role. For the case of gas flows furthermore wall slip, rarefaction or compressibility might be of the importance [7].

Gas flows can be classified depending on their corresponding Knudsen number. It relates the mean free path of the gas λ to a characteristic length scale H of the flow configuration, e.g. the diameter of a pipe:

$$\mathrm{Kn} = \frac{\lambda}{H}, \quad \lambda = \frac{kT}{\sqrt{2}\pi\sigma^2 p}. \tag{1.1}$$

In Eq. (1.1) k is the *Boltzmann* constant, T the temperature, p the pressure and σ the molecular diameter.

Only when gas flows are in the no-slip regime a continuum based description such as Navier–Stokes equations is justified. However, in the range $0.001 \leqslant \mathrm{Kn} < 0.1$ they still are applicable, if additionally slip flow and temperature jump at boundaries are applied. Their values could be computed using expressions such as those by Maxwell [14] and Smoluchowski [22]. For slip flow

* Corresponding author. Tel.: +41 316320282.
E-mail address: justyna.czerwinska@artorg.unibe.ch (J. Czerwinska).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.11.056

an analytic approach has been validated with experimental results e.g. in [9].

In certain cases viscous stresses can contribute considerable amounts of heat to the flow. The Brinkmann number can be a means to assess the influence of dissipated heat within the flowing gas,

$$Br = \frac{\mu u^2}{k(T_w - T_m)}. \tag{1.2}$$

For values $Br \ll 1$ viscous heating effects can be neglected [26]. The influence of the Brinkmann number on the heat transfer in micropipes was studied numerically for constant wall heat flux and constant wall temperature boundary conditions. With constant wall temperature the Nusselt number,

$$Nu = \frac{h_T H}{k}, \tag{1.3}$$

where h_T is the heat transfer coefficient, decreases with increasing Knudsen number [2].

When non-isothermal boundaries are present gas molecules originating from cooler regions will be moved to hotter region in the vicinity of walls. This is referred to as thermal creep or thermal transpiration flow [24].

Cases with thermal creep induced flows have been investigated before. For example [3] simulated the flow in a system of two tanks heated with different temperatures connected by the channel. Due to the temperature gradients a thermal creep flow is induced near the channel that pumps gas from the cold tank into the hot tank and later triggers a back flow. A steady state is reached when thermal creep induced pumping and back flow are balanced to a zero net mass flow (see also [10]). Linearized Boltzmann equation approach for hard sphere molecules was used to simulate the thermal creep induced flow over a flat surface with linear temperature gradient [17]. Thermal creep and thermal stress flows that both arise from non-uniform temperature distributions in gases have been studied experimentally and numerically in different applications [13,23,24,27]. The influence of gaseous slip flow on friction factor and heat transfer has been observed numerically [19]. It is shown that heat transfer is reduced when the level of rarefaction is increased [16].

Slip flows with constant-wall or constant-heat-flux wall boundary conditions have been investigated with respect to their heat transfer performance [2] as well as linear variations in wall temperature [25]. However, studies with temperature variations along more than one spatial direction have not been reported yet.

2. Setup and physical problem

A generic heat transfer device will be presented that makes use of thermal creep in microfluidic devices to form vortex structures. Due to the wall slip induced by thermal creep vortex flow patterns are obtained that shall enhance the heat transfer.

The flow is studied in a box. On two of the side walls, and on the top wall the symmetry boundary condition is set. The bottom wall is heated. At the outlet plane the pressure is set equal to the ambient pressure, at the inlet plane a mass flow as found in Table 1 was applied in all cases.

At the centre of the bottom plate the heated lattice is placed in a square area of size $a \times b$. We set size b as characteristic dimension to define the flow Knudsen number here. The aspect ratio L:d:h of the box was given with 6:4:1.5. The physical properties of the gas and the box dimensions are given in Table 1 as well as the temperature range for operation. The thermal creep flow at the solid wall is modelled using Maxwell's slip velocity boundary condition in combination with Smoluchowski's temperature jump expression.

Table 1
General gas properties, box dimensions and boundary condition values.

Property	Value
Gas constant R	287.7 J/(kg K)
Molecular diameter σ	2.7×10^{-10} m
Dynamic viscosity μ	1.7894×10^{-5} kg/(m s)
Thermal conductivity k	0.0242 W/(m K)
Specific heat ratio γ	1.4
Length L	6.0×10^{-4} m
Depth d	4.0×10^{-4} m
Height h	1.5×10^{-4} m
Lattice width L_2	6.0×10^{-6} m
Pressure difference Δp	0.001 Pa
Inlet mass flow $\dot{m}$	$6.8 \times 10^{-8} \frac{kg}{s}$
Inlet temperature T	300 K
Wall temperature, max. $T_{1\,max}$	400 K
Wall temperature, min. $T_{1\,min}$	300 K
Mean free path λ	6.8×10^{-8} m

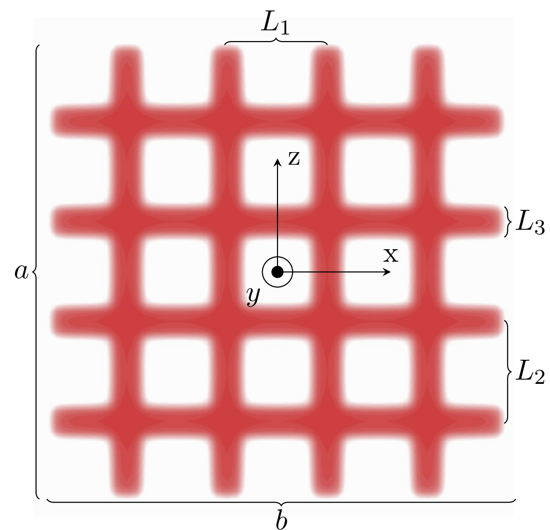

Fig. 1. Geometry of the lattice; dark regions indicate heated regions, light regions indicate the region of low wall temperature.

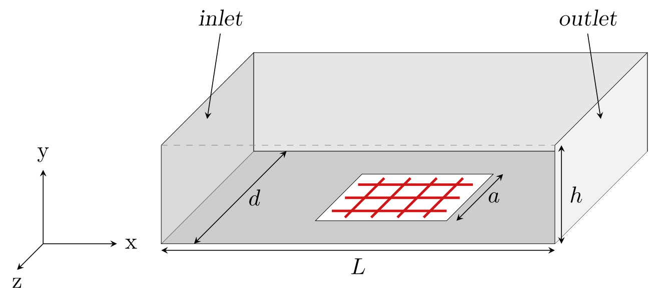

Fig. 2. Test case geometry; given dimensions are length L, depth d and height h; pressure inlet and outlet are the faces bounding x-direction; the bottom plate (min (z)) including the lattice region is a wall boundary, where the heated region is of size the $a \times b$; On all remaining faces the symmetry boundary condition is applied.

The heated lattice consists of a number of heated wires that are buried in the surface and aligned with x- and z-direction respectively. Origin of the coordinate system is in the geometrical centre of the box (see also Fig. 1).The lattice is defined by three dimensions: L_1 width in x-direction, L_2 width in z-direction and L_3 as the line thickness. The bars are defined as having a nearly plateau-like temperature maximum in the centre region, that is illustrated in Fig. 3. For the majority of cases the solid wall temperature

Download English Version:

https://daneshyari.com/en/article/657646

Download Persian Version:

https://daneshyari.com/article/657646

Daneshyari.com