Case Studies in Thermal Engineering 10 (2017) 370–381

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Effects of pressure work, viscous dissipation, shear work and axial conduction on convective heat transfer in a microtube

K.M. Ramadan

Mechanical Engineering Department, University of Sharjah, Sharjah, United Arab Emirates

A R T I C L E   I N F O

Keywords:
Viscous dissipation
Pressure work
Rarefaction
Shear work
Axial conduction

ABSTRACT

This paper investigates the effects of viscous dissipation, pressure work, shear work, rarefaction and axial heat diffusion on convective heat transfer in a microtube gaseous flow. The problem is investigated numerically for the whole flow region using a finite difference scheme and the line Gauss-Seidel iterative technique. Exact solutions of the problem in terms of temperature distribution and Nusselt number variations are also derived under fully developed flow conditions. The microtube is assumed to be sufficiently long, so that fully developed conditions are established. The analysis presented demonstrate that the effect of the boundary shear work is significant and its contribution to heat transfer can be as high as that due to heat conduction close to the upper limit of the slip flow regime. As the shear work is a result of the combined effects of viscous dissipation and pressure work at the boundary, including these effects in the analysis leads to better predictions of heat transfer phenomena. Axial heat diffusion effect on Nusselt number and the thermal entrance length are also quantified.

1. Introduction

Computations of convective heat transfer rates in micro-conduits have been the subject of numerous investigations during the past three decades. Depending on fluid flow conditions, there are many factors that can have considerable influence on predicting the heat transfer rates in micro-conduits, such as, rarefaction, viscous dissipation, pressure work, shear work, axial conduction, compressibility effects and thermal creep. Effect of pressure work and viscous dissipation on convective heat transfer of a non-slipping, pressure driven gas flow in a parallel plate channel was investigated by Ou and Cheng [1]. They concluded that for a pressure driven gas flow, these factors are significant and cannot be neglected particularly with a uniform wall temperature boundary condition. Recently, Sun and Jaluria [2–4] investigated numerically the combined effect of viscous dissipation and pressure work on heat transfer of nitrogen slip flow in long microchannels. It was found that pressure work and viscous dissipation have a significant effect on heat transfer under both slip and no-slip flow conditions. The shear work effect was however ignored in these investigations. The boundary shear work was introduced by Maslen [5] without proof or physical explanation. Using the energy conservation principle together with the kinetic theory of gases, a physical explanation for including the boundary shear work in the energy balance equation in slip flow was shown in [6]. The shear work was shown to scale with the Brinkman number in small scale channels [7] and it was concluded that the boundary shear work has been incorrectly ignored in slip-flow investigations. A study of choked flow in a parallel-plate channel with adiabatic wall boundary conditions [8] showed a good agreement between the numerical and experimental results when the boundary shear work was included in the analysis. This study was further extended for the case of a uniform wall heat flux boundary condition [9], confirming the increasing significance of the shear work with rarefaction.

Knupp et al. [10] studied the transient behavior of conjugated heat transfer in laminar microchannel flow taking into account the

---

E-mail address: kramadan@sharjah.ac.ae.

http://dx.doi.org/10.1016/j.csite.2017.09.001
Received 1 July 2017; Received in revised form 18 August 2017; Accepted 2 September 2017

Nomenclature

A	Area (m^2)
b	A constant compression parameter
Br	Brinkman number based on inlet temperature, $Br = \mu\, u_m^2/(q_w R)$
c_p	Specific heat (J/kg K)
C_1	A constant parameter, $C_1 = \beta_V Kn$
C_2	A constant parameter, $C_2 = 1 + 8C_1$
C_3	A constant parameter, $C_3 = 1 + 12C_1$
C_4	A constant parameter, $C_4 = 2\gamma\, \beta_T Kn/[(\gamma + 1)Pr]$
D	Diameter (m)
h	Convective heat transfer coefficient (W/m^2 K)
R	Microtube radius (m)
k	Thermal conductivity (W/m^2 K)
Kn	Knudsen number
$\dot{m}$	Mass flow rate (kg/s)
Nu	Nusselt number, $Nu = h\, D/k$
P	Pressure (N/m^2)
Pe	Peclet number, $Pe = Re.\, Pr$
Pr	Prandtl number, $\Pr = \nu/\alpha$
q_w	Wall heat flux (W/m^2)
Re	Reynolds number, $Re = u_m\, D/\nu$
T	Temperature (K)
T_m	Mean temperature (K)
T_i	Inlet temperature (K)
T_w	Wall temperature (K)
u	Velocity component in the z- direction (m/s)
$r,\ z$	Coordinates (m)

Greek symbols

α	Thermal diffusivity (m^2/s)
β_V	A constant parameter, $\beta_V = (2 - \sigma_V)/\sigma_V$
β_T	A constant parameter, $\beta_T = (2 - \sigma_T)/\sigma_T$
γ	Specific heat ratio
ξ	Dimensionless axial distance, $\xi = x/H$
ς	Transformed coordinate $\varsigma = 1 - 1/(1 + b\xi)$
η	Dimensionless distance, $\eta = r/R$
θ	Dimensionless temperature, $\theta(\xi,\ \eta) = (T - T_i)/(q_w R/k)$
θ_w	Dimensionless wall temperature
λ	Fluid mean free path (m)
ρ	Density (kg/m^3)
σ_T	Thermal accommodation coefficient
σ_V	Momentum accommodation coefficient
ν	Kinematic viscosity (m^2/s)
μ	Dynamic viscosity (N s/m^2)

Subscripts

c	Conduction
fd	Fully developed
m	Mean value
sw	Shear work
th	Thermal
tot	Total
w	Wall
∞	Conditions at infinity

axial conduction, and including preheating or pre-cooling of the region upstream of the heat exchange section, using the Generalized Integral Transform Technique. A numerical study of the effects of axial conduction and rarefaction in parallel plates microchannel was conducted by Kabar et al. [11]. The two-dimensional Navier–Stokes and energy equations, with slip velocity and temperature jump boundary are solved with the finite volume method. Satapathy [12] studied analytically steady heat transfer for laminar, rarefied gas flow in an infinite microtube subjected to mixed boundary conditions. The viscous dissipation, pressure work and shear work effects in these studies [10–12] are neglected.

A study of a simultaneously developing steady laminar flow under slip flow conditions inside a micro-tube is presented in [13] using the first and second-order slip flow models with a constant wall temperature boundary condition. Viscous dissipation and axial conduction effects are included in the analysis, while the pressure work and the boundary shear work are ignored. Niazmand and Rahimi [14] investigated numerically mixed convective gaseous slip flows in an open-ended vertical parallel-plate channel with symmetric and asymmetric wall heat fluxes. Pressure work and boundary shear work are also neglected in [14]. Aziz and Niedbalski [15] performed a comparative study of the first and second order slip flow models on a thermally developing dilute gas flow in a microtube with axial conduction and viscous dissipation with a constant wall temperature boundary condition. Pressure work and shear work are neglected from the analysis. Liu et al. [16] used the method of separation of variables to solve the energy equation in circular micro-channels, considering axial heat conduction, velocity slip, temperature jump, viscous dissipation and thermal entrance effects, while neglecting the pressure work and shear work. Convective heat transfer in microchannel gas flow was investigated in [17–19] considering the viscous dissipation and the boundary shear work but neglecting the pressure work term in the energy equation.

It can be concluded from this survey that in many recent studies of convective heat transfer in micro conduits the effects of viscous

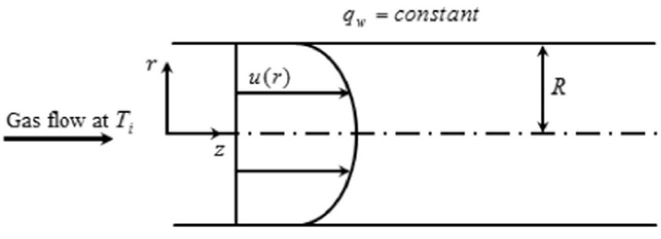

Fig. 1. Problem geometry.