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Non-isothermal slip flow over micro spherical particle at low Reynolds numbers

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HIGHLIGHTS

- Temperature jump is dominant in rarefied gas heat transfer compared to velocity slip.
- Particle temperature effect has opposite influences on flow and heat transfer.
- Compressibility effect should be considered for microscale gas flow even if Ma < 0.3.
- Gas variable properties effect cannot be neglected for non-isothermal slip flow.

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ABSTRACT

In present work, a numerical study was carried out to investigate the non-isothermal slip flow over a micro spherical particle at low Reynolds numbers. The slip boundary conditions (non-equilibrium momentum exchange and heat transfer) were adopted in the numerical model to predict the discontinuity phenomena at the gas-particle interface. It shows that the drag force acting on the particle and the average Nusselt number on the particle surface both decrease as the Knudsen number increases, which are caused by the effects of velocity slip and temperature jump on the gas-particle interface, respectively. As the particle temperature increases, the drag coefficient increases due to the increasing gas viscosity and the average Nusselt number decreases as the heat conduction becomes dominant at low Reynolds numbers. The influence of gas compressibility on the flow and heat transfer processes were studied based on the numerical predictions, which should be considered for the non-isothermal gaseous flow in the slip regime even if the Mach number is smaller than 0.3. And the effect of gas variable properties cannot be neglected as the temperature difference exists between the particle and gaseous fluid.

1. Introduction

The non-isothermal gas flow over a particle is a critical phenomenon since it has been widely involved in the chemical engineering applications, such as sedimentation (Guo et al., 2017; Wang et al., 2009), pneumatic conveying (Klinzing and Basha, 2017) and circulating fluidized bed (Cahyadi et al., 2017), etc. The studies (Acrivos and Taylor, 1962; Cheng, 2009; Feng and Michaelides, 2000; Finlayson and Olson, 1987; Whitaker, 1972) have focused on the drag force exerting on the particle and the heat transfer between particle and gas, in which the transport processes were generally treated as the macro-scale ones. With the recent rapid development in MEMS, the gas-particle fluid flows in micro-scale devices have attracted considerable attentions (Dang et al., 2014; Lee et al., 2010). As the flow characteristic length becomes comparable to the gas mean free path, the gas rarefaction effects will dominate at the gas-solid interface, which cause an obvious difference compared to the macro-scale flows. To evaluate the gas rarefaction level, the Knudsen number (Kn) can be introduced as:

$$Kn = \frac{\lambda}{L} \tag{1}$$

where, the L is the flow characteristic length and λ is the gas mean free path. For the flow in the slip regime ($0.001 < Kn \leq 0.1$), the continuity equations (such as Navier-Stokes equations) are still valid in the main flow region, however, the slip boundary conditions should be implemented in the numerical model to consider the non-equilibrium momentum exchange and heat transfer at gas-particle interface (Tao et al., 2017; Zhang et al., 2012).

Lockerby et al. (2004) studied the gas flow around a micro sphere at low Reynolds numbers (Re), in which the velocity slip

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Nomenclature

A_P	projected area of particle, m^2
C_D	drag coefficient
C_p	specific heat capacity at constant pressure, J/(kg· K)
C_v	specific heat capacity at constant volume, J/(kg·K)
d_m	collision diameter of gas molecules, m
D_p	diameter of particle, m
e	internal energy, J
E	sum of internal energy and kinetic energy, J
F_P	drag force acting on particle, N
h	heat transfer coefficient, W/(m^2·K)
H	dissipation function
k	thermal conductivity, W/(m·K)
K	Boltzmann constant, 1.380662×10^{-23}, J/K
Kn	Knudsen number
L	characteristic length, m
M	molecule weight, g/mol
Nu	average Nusselt number
Nu_l	local Nusselt number
p	pressure, Pa
P_o	operation pressure, Pa
Pe	Peclet number
Pr	Prandtl number
q	heat transfer rate, W
R	universal gas constant, J/(mol· K)
Re	Reynolds number
T	temperature, K
T_g	temperature of gas on the particle surface, K
T_{in}	incoming gas temperature, K
T_{jump}	temperature jump, K
T_p	particle temperature, K
T_w	wall temperature, K
u	velocity, m/s
u_g	velocity of gas on the particle surface, m/s
u_{in}	incoming gas velocity, m/s
u_w	wall velocity, m/s
V_{slip}	velocity slip, m/s
x	Cartesian coordinate, m

Greek symbols

γ	specific heat ratio
θ	flow angle, °
λ	gas mean free path, m
μ	dynamic viscosity, Pa · s
ρ	density, kg/m^3
ρ_{in}	incoming gas density, kg/m^3
σ_T	thermal accommodation coefficient
σ_v	tangential momentum accommodation coefficient
τ	stress, N/m^2
τ_{ij}	shear stress in the i direction, N/m^2
τ_t	tangential shear stress, N/m^2

Subscript

g	gas
in	incoming
i,j,k	directions of Cartesian coordinates
p	particle
w	wall

Superscript

$*$	non-dimensional

phenomenon was considered. They proved that the traditional Maxell's velocity slip boundary is not valid in the prediction of the flow over the sphere. And in the following work (Barber et al., 2004), it shows that the velocity slip expressed with a stress form is capable of capturing the velocity slip effect at the curved gas-solid interface. Meanwhile, a correlation of drag coefficient (C_D) considering the micro-scale effect was proposed based on the numerical results. In the work of Moshfegh et al. (2010), the laminar gas flow around a micro particle was numerically studied, in which the slip boundaries were implemented on the particle surface to consider the gas rarefaction effects in the slip regime. They found that the drag coefficient correlation with the slip factor in conjunction with the Stokes form is only valid for the extremely low Reynolds number and a drag coefficient correlation was then obtained. Feng (2010) numerically proposed a correlation for the drag force coefficient in the range of $0 < Re < 75$, in which the slip factor and Reynolds number were considered as two input parameters. In the above works, the rarefied gas was treated as the incompressible fluid even if it was at a high Reynolds number, which will lead to an inaccurate prediction of drag force coefficient. Cai and Sun (2015) numerically simulated the gas flow around a micro sphere with three different boundary conditions at the gas-particle interface, in which the gas was considered as a compressible fluid. Their results show that the no-slip boundary condition will lead to an obvious deviation compared to those with the slip boundary conditions and the gas compressibility cannot be ignored even if it was at a low Mach number in the slip regime. However, the analysis of the comprehensive comparison between the compressible and incompressible models was not provided in their work.

In the work of Kishore and Ramteke (2016), the heat transfer between fluid and micro sphere were numerically studied with the velocity slip boundary condition at the fluid-solid interface. It shows that the Nusselt number (Nu) increases with increasing slip parameter. In the following work (Ramdas Ramteke and Kishore, 2017), the Newtonian fluid flow around a sphere with the constant heat flux was studied and a Nusselt number correlation was obtained. It should be noted that the temperature jump on the fluid-particle interface was not considered in these studies, which will lead an overvalued prediction of the heat transfer rate. In the work of Anbarsooz and Niazmand (2015), both velocity slip and temperature jump boundary conditions were implemented on the particle surface to simulate the Newtonian fluid flow around a sphere. However, it should be pointed out that constant gas properties were used in their model, which led to a deviation in calculating the heat transfer rate at the high Reynolds number and high Prandtl number (Pr). With the consideration of gas variable properties, Mohajer et al. (2015) investigated the drag force and heat transfer rate on the micro sphere surface with the velocity slip and temperature jump boundary conditions for the low Reynolds number flow ($Re < 3$). They found that the velocity slip and temperature jump will affect the heat transfer between gas and particle in an opposite way. An incompressible idea gas model was adopted in the analysis of the gas variable properties effect, however, the effect of compressibility caused by the variable pressure was not considered in their work.

Table 1 presents a summary of the previous studies on gas-particle slip flow and heat transfer. It can be found that few studies clarified the comprehensive mechanism of gas rarefaction effects (velocity slip and temperature jump) on the flow and heat transfer