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New correlations for slip flow and heat transfer over a micro spherical particle in gaseous fluid

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ABSTRACT

In this work, a numerical model was established to simulate the gas flow and heat transfer over a micro spherical particle in the slip regime, in which the gas rarefaction effects (slip phenomena and gas compressibility) and temperature-dependent properties were considered. The Navier-Stokes equations and energy equation were adopted to govern the gas flow and heat transfer in the continuum region, for which the velocity slip and temperature jump boundary conditions were implemented at the gas-particle interface to predict the slip phenomena. The influences of the gas compressibility and temperature-dependent properties on the gas flow and heat transfer characteristics were investigated based on the numerical predictions. It shows that the drag force and heat transfer rate on the particle surface decrease due to the gas velocity slip and temperature jump, respectively. The drag force acting on the particle surface increases with the increase of particle temperature, which is caused by the increasing viscosity of the gas around the particle. The heat transfer coefficient decreases as the particle temperature increases, which is caused by the increasing thermal resistance due to the increase of temperature jump. Finally, the novel correlations for drag coefficient and Nusselt number of the rarefied gas flow over a micro spherical particle were proposed, which consider the influences of the gas rarefaction effects and temperature-dependent properties.

1. Introduction

The gas-particle fluid flow widely exists in the industrial applications [1–3], such as circulating fluidized bed [4], spraying coating process [5] and pneumatic conveying [6], which is generally treated as the macro-scale one. With the rapid development of MEMS technique in recent years, the micro-scale gas-particle fluid flow in the small devices, such as micro-fluidized bed [7] and micro propellant thruster [8,9], has attracted considerable attentions. As the flow characteristic length (L) becomes comparable to the gas mean free path (λ) in these small devices, the flow and heat transfer characteristics will show a significant difference compared to that in the macro-scale one, which is caused by the gas rarefaction effects. To describe the rarefaction level, the Knudsen number (Kn), which is defined as the ratio of gas mean free path to characteristic length, is introduced as:

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

For the gas flow in the slip regime ($0.001 < Kn \leq 0.1$), the main flow region is still governed by the conservation equations (Navier-Stokes equations and energy equation), while the non-equilibrium effect dominates at the gas-solid interface [10]. Thus, the precise description of the non-equilibrium momentum exchange (velocity slip) and heat transfer (temperature jump) at the gas-particle interface becomes one challenging issue in the prediction of the micro-scale gas-particle flow.

In the work of Afshar et al. [11], an Eulerian-Lagrangian approach with the velocity slip boundary condition implemented on the wall was adopted to simulate the gas-particle flow in a microchannel. The result shows that heat transfer between upper and lower walls increases as the nanoparticles are homogenously added into the flow without any additional pressure drop. Hosseini et al. [12] numerically simulated the particles deposition in a converging-diverging microchannel, in which the velocity slip boundary condition was implemented on the channel wall. It shows that the gravity force dominates the deposition of the particles with diameters ranging from 0.1 μm to 1 μm. The diffusion effect becomes obvious for the particles with diameters of 0.001–0.1 μm. In the study of Kishore [13], the drag force acting on the tandem particles was studied with the application of the liner velocity slip boundary on the channel wall. The influences of Reynolds number (Re), particle aspect ratio and inter particle distance on the flow pattern and drag force were investigated. The results show that drag coefficient (C_D) increases with increasing the inter particle distance for different Reynolds numbers and particle aspect ratios. However, the slip boundary on the wall was simply set as the inlet

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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)
d_m	collision diameter of gas molecules, m
D_p	diameter of particle, m
F_P	drag force acting on particle, N
h_θ	local convective heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
K	Boltzmann constant, 1.380662×10^{-23}
Kn	Knudsen number
H	height, m
L	characteristic length, m
M_w	molecule weight, g/mol
Nu	Nusselt number
Nu_{avg}	average Nusselt number
Nu_θ	local Nusselt number
p	pressure, Pa
Pe	Peclet number
Pr	Prandtl number
q_t	tangential heat transfer rate on the particle surface, W/m^2
q_θ	local heat transfer rate, W/m^2
r	r coordinate, m
R	universal gas constant, J/(mol K)
Re	Reynolds number
R_∞	radius of computation domain, m
T	temperature, K
T_g	temperature of gas on the particle surface, K
T_{in}	incoming gas temperature, K
T_{jump}	temperature jump, K
$T_{jump,\ avg}$	average temperature jump, K
T_p	particle temperature, K
T_w	wall temperature, K
T'	dimensionless temperature
T^*	dimensionless temperature
U^*	dimensionless velocity
v	velocity, m/s
v'	dimensionless velocity
v_g	velocity of gas on the particle surface, m/s
v_{in}	incoming gas velocity, m/s
v_r	velocity in r direction, m/s
v_w	wall velocity, m/s
v_θ	velocity in θ direction, m/s
V_{slip}	velocity slip, m/s
$V_{slip,\ avg}$	average velocity slip, m/s

Greek symbols

γ	specific heat ratio
θ	θ coordinate, °
τ	stress, N/m^2
τ_{rr}	normal stress in r direction, N/m^2
$\tau_{r\theta}$	shear stress in r direction, N/m^2
τ_t	tangential shear stress, N/m^2
$\tau_{\theta r}$	shear stress in θ direction, N/m^2
$\tau_{\theta\theta}$	normal stress in θ direction, N/m^2
λ	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

Subscript

avg	average
g	gas
in	incoming, inlet
op	operation
out	outlet
p	particle

Superscript

*	non-dimensional
'	non-dimensional

velocity in Kishore's model. The velocity slip boundary condition was only applied on the microchannel wall in the above studies and the velocity slip at the gas-particle interface was not included in these numerical models, which will lead to an inaccurate prediction of the gas-particle transport in the slip regime. In the work of Moshfegh et al. [14], a numerical model considering the velocity slip on micro particle surface was established to calculate the drag force. It is found that the drag force decreases as increasing the Knudsen number, and a correlation for the drag coefficient of the gas flow over a micro sphere was proposed. Feng et al. [15] obtained a correlation for the gas flow over a sphere, in which the slip coefficient was used to consider the gas rarefaction effects instead of the implementation of the velocity slip boundary condition. It should be noted that the influences of the gas compressibility and non-isothermal flow were neglected in these two numerical models. In Loth's work [16], an analytical drag coefficient correlation was proposed, which considers the effects of gas rarefication and compressibility. It reported that the drag is dominated by the gas rarefication effect as $Re < 45$, while the drag is dominated by the gas compressibility as $Re > 45$.

In the work of Kishore and Ramteke [17], the heat transfer between the fluid and the micro sphere were numerically studied utilizing the velocity slip boundary condition at the fluid-solid interface. It shows that the average Nusselt number (Nu_{avg}) increases with increasing the slip parameter and a correlation for average Nusselt number was then proposed. It should be noted that the temperature jump on the gas-particle interface was not considered in the above model, which will lead to an overvalued prediction of the heat transfer rate. Mohajer et al. [18] 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 ($Re < 3$). It can be found that the variable properties, such as dynamic viscosity and thermal conductivity, have significant influences on the flow and heat transfer processes. It should be pointed out that the gas density should vary with the temperature and the compressibility in micro scale flow cannot be neglected even if the Mach number is <0.3 [19], which were not considered in the above studies.

In this paper, the flow and heat transfer characteristics of the gas flow over a spherical particle in the slip regime were numerically studied. To consider the gas rarefaction effects, the velocity slip and temperature jump boundary conditions were implemented on the particle surface in the numerical model. In addition, the effects of the gas compressibility and temperature-dependent variable properties (such as density, dynamic viscosity and thermal conductivity) were included in the numerical modeling. The influences of Knudsen number and particle temperature (T_p) on the drag force and heat transfer rate on particle surface were thoroughly analyzed based on the numerical predictions. Finally, the new drag coefficient correlation and average Nusselt number correlation for the rarefied gas flow over a micro spherical particle were proposed in this work.