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Numerical study on flow and heat transfer characteristics of low pressure gas in slip flow regime

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ABSTRACT

The flow and heat transfer characteristics in slip flow regime at low pressure state are numerically investigated by using CFD solver. The complete boundary conditions of first-order velocity slip are considered by User Defined Functions (UDFs), which include effects of thermal creep and wall curvature, as well as temperature jump. Based on the dimensionless continuity, momentum and energy equations along with these boundary conditions, the numerical simulation for flow and heat transfer behaviors over a circular cylinder is conducted in a wide range of Re = 0.001 to 20 and Kn = 0.01 to 0.1. It is found that the prediction results without considering the slip boundary conditions obviously deviate from the experimental values with the increase of Knudsen number, while the one by the developed model is in good agreement with the experimental results. Meanwhile, the variation of physical fields under different Reynolds and Knudsen numbers is discussed in detail. The empirical correlations in the slip flow regime for predicting average drag coefficient and average Nusselt number are proposed on the basis of simulation data, which makes the traditional method used for continuous flow regime be successfully applied into the prediction of flow and heat transfer performances in the slip flow regime.

1. Introduction

The flow and heat transfer characteristics in the slip flow regime of low pressure gas are of increased interest due to the development of industry, such as large vacuum chambers, vacuum tunnels, hot-wire anemometers in low density environment, launch vehicles passing through atmospheric, landers on Mars et al. In those cases, owing to decrease of air pressure, a Knudsen layer between air and wall surface will form, and a slip phenomenon occurs, i.e. velocity slip and temperature jump. Tsien [1] and Schaaf [2] originally proposed that the flow regimes of gas could be classified as continuum flow ($Kn < 0.01$), slip flow ($0.01 \leq Kn \leq 0.1$), transition flow ($0.1 \leq Kn \leq 10$) and free molecular flow ($10 \leq Kn$) in terms of the degree of rarefaction, which is generally determined by Knudsen number. Knudsen number is defined as the ratio of mean free path to characteristic length, as vividly shown in Fig. 1.

The classical problem of fluid flow and heat transfer over a circular cylinder has been the hot subject of much research in the past. In the early work, the flow and heat transfer behaviors over the cylinder were investigated by experimental methods. King [3] conducted study on the heat transfer of hot-wire anemometry, and correlated the earliest empirical correlation. Hilpert [4] presented an empirical correlation of wide range to meet industrial demand at that time. The range of his correlation for Reynolds number is from 0.4 to 4×10^5. After that several researchers [5–15] have conducted study on broadening application scope for Reynolds number and Prandtl number to meet practical requirements, such as lower Reynolds number, higher Reynolds number and fluid properties et al. Collis [5] measured the heat transfer from circular wires placed normal to a horizontal airstream in the Reynolds number range from 0.01 to 140. He indicated free convection heat transfer for horizontal wires becomes significant, when the Reynolds number is less than the cube root of Grashof number. Fand [7] developed a uniform empirical correlation for Reynolds number in the range from 0.01 to 2×10^5 to avoid the difficulty of choosing coefficient at different Reynolds numbers. Tritton [8] experimentally studied the flow past the circular cylinder in the Reynolds number range from 0.5 to 100, and measured the drag force on the circular cylinder. Zukauskas [12] conducted extensive experimental study on both tube bundles of various arrangements and a single tube in crossflow in the Prandtl number range from 0.7 to 500 and the Reynolds number range from 1 to 2×10^6.

With the computational fluid dynamics (CFD) technology maturing, the numerical study of flow and heat transfer around circular cylinders

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Nomenclature

u	velocity component in x direction, m/s
v	velocity component in y direction, m/s
u_∞	free stream velocity, m/s
u_n	gas velocity normal to the wall, m/s
u_s	gas velocity tangential to the wall, m/s
u^*	dimensionless velocity component along x direction
v^*	dimensionless velocity component along y direction
h_{loc}	local heat transfer coefficient
x, y	Cartesian coordinates
s, n	natural coordinates
r, θ	polar coordinates
p	gas pressure, Pa
p_∞	free stream static pressure, Pa
p^*	dimensionless pressure
q_{loc}	local heat flux density, W/m^2
A	frontal area, m^2
C_D	average drag coefficient
D	diameter of the circular cylinder, m
F_D	total drag, N
L_m	molecular mean free path, m
T	gas temperature, K
T_∞	free stream temperature, K
T_f	film temperature, K
T_s	gas temperature adjacent to wall surface, K
T^*	dimensionless temperature
Re	Reynolds number, $\mathrm{Re} = uD/\nu$
Kn	Knudsen number, $Kn = L_m/D$
Gr	Grashof number, $Gr = g\beta D^3 \triangle T/\nu^2$
Pr	Prandtl number, $\mathrm{Pr} = \mu c_p/\lambda$
Ec	Eckert number, $\mathrm{Ec} = u^2/(c_p \triangle T)$

Greek symbols

ρ	gas density, kg/m^3
α	angle that outer normal of dA makes with positive flow direction
τ_w	shear force around a circular cylinder, N
σ_m	momentum accommodation coefficient
σ_T	thermal accommodation coefficient
γ	specific heat ratio
μ	dynamic viscosity coefficient of gas, Pa·s
ν	kinematic viscosity of gas, m^2/s

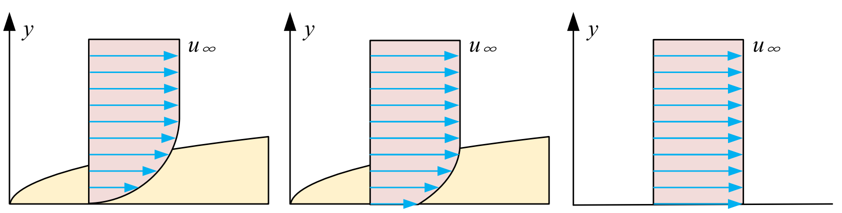

Fig. 1. Schematic of gas flow regimes.

becomes possible, thus many investigators [16–19] have conducted extensive research. Lange [16] systematically carried out numerical investigation on the two-dimensional flow around a heated circular cylinder located in laminar crossflow for the Reynolds number range of $1 \times 10^{-4} \le \mathrm{Re} \le 200$ and for temperature loading of 1.003–1.5. Bharti [17] numerically solved the momentum equations and described the steady cross-flow of power law fluids past an unconfined circular cylinder. He presented that both Reynolds number and power law index had great effect on the flow characteristics over conditions of wide range as $5 \le \mathrm{Re} \le 40$ and $0.6 \le n \le 2$.

Although many researches have done a lot of work on the fluid flow and heat transfer characteristics over the circular cylinder, little attention has been paid in the slip flow regime at low pressure state. Nevertheless, numerous investigations [20–27] have been conducted on the flow and heat transfer behaviors of micro-scale devices such as micro-channels or other shapes such as small particles, which have demonstrated that the continuum Navier-Stokes equations are still valid in the bulk flow in the slip flow regime, but the fluid near the wall surface is no longer in the state of local thermodynamic equilibrium, i.e. the so-call Knudsen layer. In this regime, various rarefaction effects could emerge, including the presence of non-negligible velocity slip and temperature jump on the wall surface [28,29]. Du [23] carried out numerical simulation to study the effect of weak rarefaction on the characteristics of turbulent flow in micro-channels. He introduced a slip boundary condition in the simulation of fluid flow to account for the effect of weak rarefaction. It was found that the weak rarefied turbulent flow had higher streamwise velocities over the entire channel width. Lockerby [24] reported that the Maxwell's original slip boundary condition was widely misapplied in current rarefied gas flow calculations. He indicated that if its commonly-accepted form (as shown in Eq. (1)) were applied to the simulation of gas flow over curved or moving surfaces, crucial physics could be lost. However, few studies have been done on the computational fluid dynamics method considering the complete form of velocity slip boundary condition in curved surface, since several problems have been not solved in the solver, such as coordinate transformation, UDFs development, solution divergence et al. Leontidis [27] developed a numerical procedure to model 2D thermal creep flow by Fluent solver. The boundary conditions, which included first order velocity slip and temperature jump, were implemented via C routines. They presented that micropumps were efficient in the slip flow regime. Meanwhile, several researchers [30,31] also investigated the heat transfer enhancement of nanofluids in the slip flow regime using the lattice Boltzmann method (LBM). They demonstrated that the LBM can be used to simulate the heat transfer of nanofluids in the slip flow regime, and found that the decrease of slip coefficient may enhance the convective heat transfer coefficient. Although the effect of fluid slip in above literatures has been considered, no work has been done on the fluid flow and heat transfer behaviors over the circular cylinder using finite volume method (FVM) based commercial CFD solver Fluent, as well as considering the complete first-order velocity slip form.

$$u_s = \frac{2-\sigma_m}{\sigma_m} L_m \frac{\partial u_x}{\partial n} \tag{1}$$

where u_s is the x-component of slip velocity, u_x is the gas velocity tangential to the wall, n is the coordinate normal to the wall, and σ_m is the momentum accommodation coefficient.