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Numerical Study of Flow and Heat Transfer around Single Smooth or Dimpled Sphere in the Square Channel

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ABSTRACT

The purpose of present paper is to investigate the flow and heat transfer characteristics of single smooth or dimpled sphere in the square channel by numerical simulation. Three-dimensional Navier-Stokes equations and SST k-ω turbulence model are adopted for the simulations. The effects of channel to particle diameter ratio and particle surface shape were discussed and presented in the present paper. It is found that, with the same inlet velocity and particle surface shape, when the ratio of channel to particle diameter is less than 4, as W/D decreases, the drag coefficient and Nusselt number increases rapidly. In addition, compared with smooth sphere particles, the presence of dimples decrease flow drag. Furthermore, at Re=29000, although there is little difference of Nusselt number between smooth and dimpled particles, the surface heat transfer characteristics of different particles are quite different.

Keywords: Dimpled sphere, flow around single sphere, heat transfer, numerical simulation

NOMENCLATURE

Abbreviations	
PIV	particle image velocimetry
SST	shear-stress transport
Symbols	
b	distance between dimples, mm
c	width of dimple, mm
C_d	drag coefficient
D	particle diameter, mm
k	depth of dimple, mm or turbulence kinetic energy, $m^2 \cdot s^{-2}$
L_1	inlet distance, mm
L_2	outlet distance, mm
L	length of square channel, mm
N_d	dimple number of sphere surface
Nu	Nusselt number
P	pressure, Pa
Q	heat flux, $W \cdot m^{-2}$
Re	Reynolds number
T_0	inlet temperature, K
T_p	particle surface temperature, K
u_0	velocity in the main flow direction, $m \cdot s^{-1}$
W	width of square channel, mm
y^+	dimensionless wall distance
M	dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
μ_t	turbulent dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
P	density, $kg \cdot m^{-3}$
Ω	specific dissipation rate, s^{-1}

1. INTRODUCTION

As the passive drag reduction technology, dimple structure has been widely investigated and applied to reduce flow drag in recent years. Libii [1] designed and measured the experiment to study the drag coefficient of fluid flows past the golf balls. The research found that the presence of dimples delayed the separation of the boundary layer and reduced the flow wake region. Aoki et al. [2] experimentally investigated the influence of flying speeds, rotational frequencies and surface shapes on the aerodynamic characteristics of golf balls. They found that for any spheres with dimples, there exist the subcritical, critical and supercritical regions. Choi et al. [3] researched that the fluid flowed around a dimpled sphere, and the mechanism of drag reduction was revealed. However, most of the researches for the aerodynamic on the dimpled sphere were carried out in the large space, which were regardless of the influence of the channel to particle diameter ratios on flow drag.

Dimple structure are researched and applied as the heat transfer enhancement technology in many fields because there is no need of additional equipment. The

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dimple structure applied to the flat plate were investigated by Afanasyev et al. [4]. They found that the dimple structure could not only increase effective heat transfer area, but also break boundary layers. Rao et al. [5] numerically and experimentally investigated the flow and heat transfer characteristics of different dimpled surfaces. Yang et al. [6] investigated structured packed beds with dimple particles for the first time and found that dimple structure improved the overall heat transfer efficiency. However, the mechanism of the influence of dimple structure on heat transfer was still not clear, especially for the dimple structure on the ball.

In the present paper, the flow and heat transfer characteristics of single smooth or dimpled sphere in the square channel are numerically investigated. The effects of different channel to particle diameter ratios and particle surface shapes were compared and analyzed in detail at *Re*=29000.

2. PHYSICAL MODEL AND COMPUTATIONAL METHOD

2.1 Physical model

As shown in Fig. 1, a smooth or dimpled sphere particle is arranged in the square channel, and the channel to particle diameter ratios (*W/D*) are controlled by changing the size of width (*W*), where *W* is the square channel width, and *D* is the sphere diameter which is kept at 42.6 mm. L_1 and L_2 are provided to ensure full development of inlet and outlet flow, and the sizes are 213 mm and 690.13 mm respectively. Air is used as the cold fluid, and the inlet temperature and velocity are T_0 and u_0 respectively. The wall of the square channel is kept adiabatic. Meanwhile, the wall of the particle is fixed at T_p. The model and dimensions of sphere particle with dimples are presented in Fig. 2 and Table 1. While N_d is the number of dimples on the surface of the sphere particle.

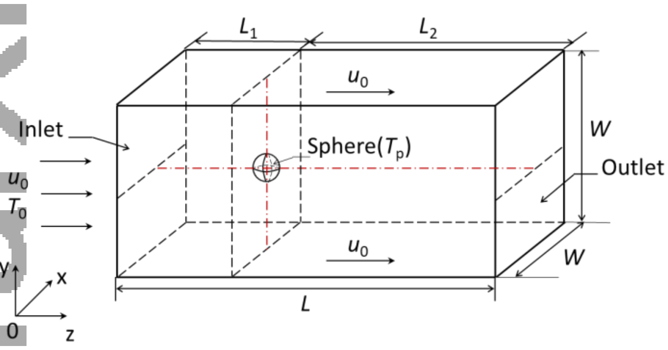

Fig. 1. Physical model and computational domain.

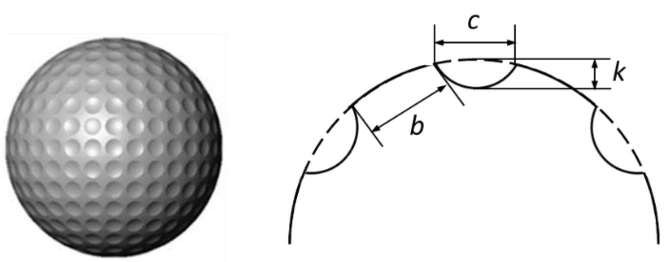

Fig. 2. Detailed information for dimpled sphere.

Table 1

Typical geometrical parameters for dimpled sphere

N_d	*b* (mm)	*c* (mm)	*k* (mm)
184	2.043	3.528	0.338

2.2 Governing equations and computational methods

Three-dimensional Navier-Stokes and energy equations were used in this research for the steady-state incompressible flow. The Reynolds number (*Re*) is fixed at 29000, which is situated in the drag subcritical region for the flow past a single dimpled sphere as reported by Aoki et al [2]. The SST *k-ω* turbulence model was chosen to simulate the turbulent flow. The conservation equations for mass, momentum and energy are as follows:

Continuity:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Momentum:

$$\rho\frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[(\mu+\mu_t)(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] \tag{2}$$

Energy:

$$\rho\frac{\partial u_i T}{\partial x_i} = \frac{\partial}{\partial x_j}[(\frac{\lambda}{c_p} + \frac{\mu_t}{\sigma_T})\frac{\partial T}{\partial x_j}] \tag{3}$$

Furthermore, in this work, Reynolds number (*Re*) based on inlet flow velocity (u_0) and particle diameter (*D*) is adopted. The parameters of study mainly include drag coefficient (C_d) and Nusselt number (*Nu*), which are defined as follows:

$$Re = \frac{\rho u_0 D}{\mu} \tag{4}$$

$$C_d = \frac{2F_d}{\rho u_0^2 D} \tag{5}$$

$$Nu = \frac{Q}{\pi D(T_p - T_0)\lambda} \tag{6}$$

where ρ is the density of air, μ is the viscosity of air, F_d is the flow drag, *Q* is the total heat flux on the surface of the sphere particle and λ is the thermal conductivity of air.

The commercial software ANSYS FLUENT 14.5 was used for numerical calculation. At the inlet, the temperature of air is 293 K and the velocity is constant at *Re*=29000. The pressure-outlet is adopted at outlet boundary. The particle surface temperature is set to 323 K and the channel walls are adiabatic. Moreover, the wall surface adopts no slip condition. The SIMPLE method is used to couple the velocities and pressure, and second order upwind scheme is used for the convective terms in the momentum, energy and turbulence equations to reduce numerical errors. Furthermore, the residual of the calculation is less than 10^{-5}.

3. COMPUTATIONAL GRID AND MODEL VALIDATION

In this calculation, a sphere particle with the number of dimples of 184 was selected for grid independence and model validation. A tetrahedral mesh was used in this simulation because of the geometric complexity of the surface of dimpled sphere particles. Furthermore, aiming to the requirements of SST *k-ω* turbulence model on wall surface grid (y^+<1), very thin prismatic boundary layers were used for wall surface mesh optimization. By changing the maximum grid size and the height of the first layer of the prismatic boundary layer, six grids ranging from 3×10^4 to 3×10^5 were used. Finally, the drag coefficient and Nusselt number difference between the fifth set of grids and the sixth set of grids are 0.25% and 1.17%, respectively. Therefore, the grid independent solution is considered to be obtained.

The validation of the simulation method is based on the calculation of flow around single sphere. The results of drag coefficient were compared with the experimental values of Aoki et al. [2], and the maximum deviation is 11.7%. When *Re* is 2069 and 5157, the *Nu* and C_d of flow around single smooth ball were calculated and compared with the results of Dixon et al. [7], and the deviations are within 10%. Therefore, the present computational model and methods are reliable for simulations of flow and heat transfer past spheres.

4. RESULTS AND DISCUSSIONS

In this section, when *Re*=29000, the variation of drag coefficient and Nusselt number with the channel to particle size ratio is shown in Fig. 3. It can be clearly seen that both the flow around smooth and dimpled single sphere, when *W/D* is less than 4, as *W/D* decreases, the C_d and *Nu* increase rapidly. This shows that when the ratio of square channel to particle diameter is less than 4, the channel wall surface has a greater influence on the flow and heat transfer characteristics. Furthermore, throughout the research, compared with smooth sphere, when air flows around dimpled sphere, the C_d and *Nu* are lower.

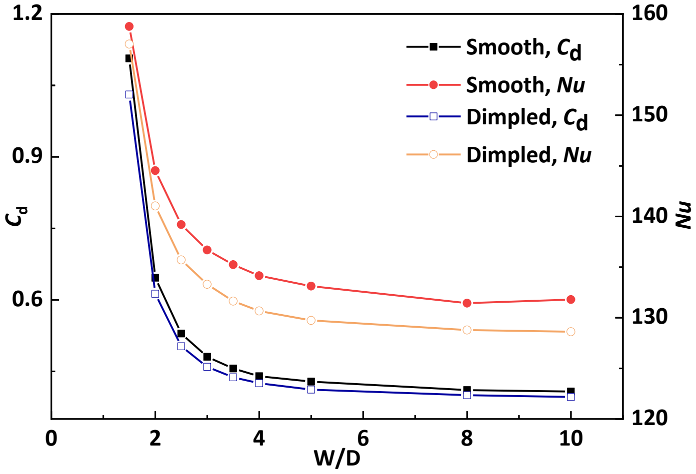

Fig. 3. The C_d and *Nu* for different channel to particle size ratios (*Re*=29000)

When *W/D*=1.5, the velocity contour and flow separation angle of the sphere particle around the flow direction are shown in Fig. 4. The flow separation angle is defined as the angle between the flow separation point and the stagnation point at the longitudinal middle section. When *Re*=29000, the flow contour of the smooth sphere and the dimpled sphere have very little difference, but the flow separation point of the dimpled sphere is delayed. As a result, the increase of the separation angle brings the decrease of flow drag. Therefore, the existence of dimples on the surface of particle delay the separation of turbulent boundary layer and reduce the flow drag.

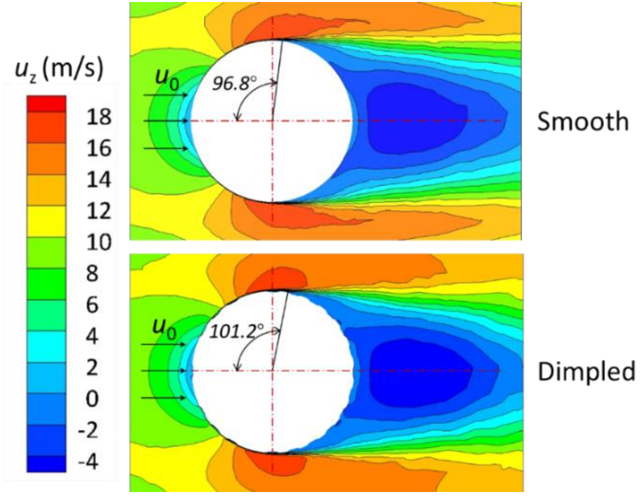

Fig. 4. W/D=1.5, the velocity contour and flow separation angle near the particle surface

The heat transfer characteristics of smooth and dimpled sphere particles with three different channel to particle size ratios were investigated. Firstly, at W/D=1.5, 4, 8, the Nu of sphere particles with different surface structures were compared, as shown in Table 2. The Nu of the dimpled particle is slightly smaller than that of the smooth particle, moreover the maximum deviation is within 3%. This indicates that the heat transfer capacity of dimpled particles and smooth particles with different W/D is slightly smaller at Re=29000. Secondly, the heat transfer contour on the surface of the sphere particles are shown in Fig. 5. Owing to the heat transfer worsen caused by the expanding of laminar boundary layer, it can be seen that there is an annular section with significantly less heat transfer on the surface of the particles. Furthermore, due to the existence of dimples on the surface of particles, although there is little difference in Nu between smooth particles and dimpled particles, the local surface heat transfer characteristics are very different. The heat transfer capacity of each dimple interior is weakened because of flow stagnation or backflow. However, after flowing through the dimples, the mainstream fluid attaches to the surface of the sphere particles surface, so there is a semilunar region with more heat exchange behind each dimple.

Table 2

Re=29000, the Nu of smooth and dimpled particles

W/D	Smooth Nu	Dimpled Nu
1.5	158.8	157.1
4	134.1	130.7
8	131.4	128.8

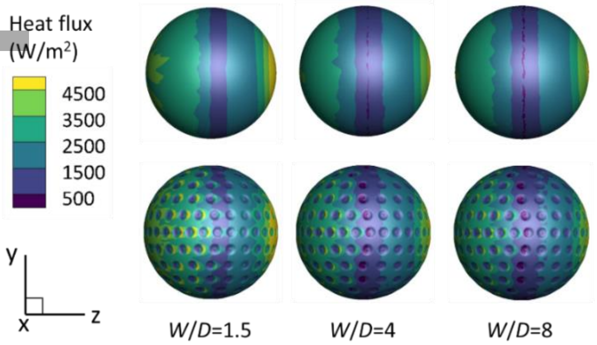

Fig. 5. Re=29000, the Nu contour of particle surfaces

5. CONCLUSIONS

In the present study, the flow and heat transfer characteristics of the air flows past single particles were numerically investigated at Re=29000, and the main results are as follows:

(1) Under the condition of large channel to particle size ratio (W/D>4) and under the condition of smaller channel to particle size ratio (W/D≤4), the flow and heat transfer characteristics of single particles are quitely different. When W/D≤4, the C_d and Nu of flowing around particles increase significantly with the decrease of W/D. Therefore, when the channel to particle size ratio is relatively small (W/D≤4), for the fluid flows past particles, the influence of the channel wall surface on the flow and heat transfer characteristics must be considered.

(2) At Re=29000, although there is little difference of Nu between the smooth particles and dimpled particles, the surface heat transfer characteristics of particles have a huge distinction. In addition, the presence of dimples can reduce the flow drag.

ACKNOWLEDGEMENT

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