Technique for measurements of the drag coefficient of spherical particle at condition of gas injection from its surface

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Abstract. A new technique for measurement of the drag coefficient of spherical particle at condition of gas injection from its surface is presented. Results of investigation of the effect of the gas injection from a surface of a solid spherical particle on the drag coefficient are presented. In the investigation, the ratio of the gas injection rate and the velocity of the flow blowing around the particle was varied. Based on the obtained results, it is shown that the drag coefficient in the absence of the gas injection from the particle surface in the examined range of the Reynolds numbers are consistent with the standard drag dependence for the turbulent flow regime. At the same time, when at condition of gas injection from the particle surface, the drag coefficient is decreased (this effect is more pronounced with a decrease in the flow rate). The dependences of the change in the drag coefficient on the Reynolds number with changing the rate of the gas injection from the particle surface.

1. Introduction

The processes of motion of condensed (solid or liquid) particles in a gas flow are of practical importance in a number of engineering and technology branches, in which two-phase flows of the operation medium are implemented [1]. One of the main characteristics determining the trends of motion of particles in a two-phase flow is the drag coefficient $C_x$. The common drag curve (the dependence of $C_x$ on the Reynolds number) and most theoretical and empirical dependencies for $C_x$ presented in the literature are obtained without taking into account conditions the gas injection from the particle surface [2, 3].

In a number of practically important problems, intense injection of gaseous products of evaporation and/or particle combustion from the particle surface (movement of burning coal particles in furnace devices, burning of liquid fuel droplets in combustion chambers of aircraft and rocket motors, and evaporation of sprayed water during aircraft fire extinguishing, etc. [4–6]) occurs. Under the conditions of the gas injection from the particle surface into a carrier medium, the use of a common drag curve leads to errors in calculating the particle velocity [2].

Experimental data from various authors show that the evaporation or burning of a particle substance reduces significantly the drag coefficient [7]. In analysis of the published results, it should be taken into account that the data are obtained, as a rule, in the presence of particle acceleration. Wherein, it is rather difficult to distinguish the effect of the mass flow from the particle surface in a pure form.

In the present work, a new technique for measurement of the drag coefficient of spherical particle at condition of gas injection from its surface, is presented [8].

2. The scheme of the experimental setup
The scheme of the experimental setup for measuring the drag coefficient of a spherical particle at condition the gas injection from its surface is proposed in figure 1 [8]. The hollow spherical particle 1 with a porous shell mounted on the console 2. The console made in the form of a hollow tube, allows the compressed gas to be supplied through it into the particle cavity. At the same time, with is provided the gas to be uniformly injected from its surface. The console is fixed on a ball bearing 3 and can rotate around the horizontal axis perpendicular to the direction of the blowing gas flow (figure 1). The upper part of the console is made in the form of the arrow 4, which allows the rotation angle of the console to be measured on the scale 5 when the particle is deflected upon the exposure to the gas flow. The blowing gas flow velocity is measured with the Pitot tube 6 [9].

![Figure 1. The scheme of the experimental setup.](image)

When carrying out measuring the compressed air is supplied into the internal cavity of the particle 1 with the flexible hose 7 from the cylinder 8 through the gas reducer 9 equipped with the test-pressure gauge 10. The volumetric flow rate of the air injected into the particle cavity is measured with the SG-6 turbine flow meter [10]. Varying the flow rate of the air blown through the particle surface allows the dependence of the drag coefficient of the spherical particle on the injection intensity (the Reynolds number Re) to be determined for the given velocity of the gas flow blowing the particle characterized by the Reynolds number Re0.

3. Testing the method
To test the proposed method, a series of experiments were performed to investigate the drag coefficient of a spherical particle upon the gas injection from its surface. In the experiments, a hollow perforated spherical particle with a diameter $D_p = 40$ mm and a mass $m_p = 2.71$ g was used.

The pressure drop $\Delta p$ was determined using the Pitot tube. The air flow velocity was determined by the following formula:
\[ u = \sqrt{\frac{2 \Delta p}{\rho}}, \]  

where \( \rho = 1.205 \text{ kg/m}^3 \) is the air density at a temperature of 20°C.

The formula for calculating the drag coefficient is:

\[ C_x = \frac{8 m_p g}{\pi D_p^2 \rho u^2} \cdot \tan \alpha, \]  

where \( g \) is the acceleration of gravity; \( \alpha \) is the measured angle of the console deviation from the vertical.

At the first stage of the experiments, the drag coefficient of the particle was measured in the absence of the gas injection from its surface. The results of the measurements are presented in Table 1.

Table 1. Results of measurements of the drag coefficient of the particle in the absence of gas injection from its surface.

| \( u \), m/s | 1.18 | 1.66 | 2.05 | 2.37 | 2.65 | 3.12 | 3.73 |
|---|---|---|---|---|---|---|---|
| \( \alpha \), deg | 1 | 2 | 3 | 4 | 5 | 7 | 10 |
| \( C_{xo} \) | 0.441 | 0.443 | 0.436 | 0.438 | 0.439 | 0.442 | 0.444 |
| \( \text{Re} \cdot 10^{-3} \) | 3.139 | 4.430 | 5.470 | 6.304 | 7.043 | 8.316 | 9.943 |

Table 1 presents the measured velocity \( u \) of the blowing gas (air) and the angle \( \alpha \) of the console deviation, as well as the calculated drag coefficient \( C_{xo} \) and the Reynolds number:

\[ \text{Re}_0 = \frac{\rho u D_p}{\mu}, \]  

where \( \mu = 1.81 \cdot 10^{-5} \text{ Pa} \cdot \text{s} \) – coefficient of dynamic viscosity air at a temperature of 20°C.

The obtained drag coefficient in the range of the Reynolds numbers \( \text{Re}_0 = (3.14 \div 9.94) \cdot 10^3 \) are consistent with the common dependence [11] for the turbulent flow regime (\( C_{xo} = 0.44 \) at \( \text{Re}_0 > 10^3 \)).

In the second series of experiments, the particle drag coefficient was measured upon the gas injection from its surface with a volumetric flow rate \( Q = 0.350 \cdot 10^{-3} \text{ m}^3/\text{s} \) and \( Q = 0.525 \cdot 10^{-3} \text{ m}^3/\text{s} \) for the given flow velocity \( u = 1.66 \text{ m/s} \) and \( u = 2.65 \text{ m/s} \), respectively. The results of the measurements are presented in Table 2.

Table 2 presents the calculated velocity \( u_s \) of the injected gas and the Reynolds number of the gas flow from the particle surface:

\[ \text{Re}_s = \frac{\rho u_s D_p}{\mu}. \]  

The velocity of the injected gas (air) was calculated from the measured volumetric flow rate \( Q \) and the total cross-sectional area \( S \) of perforations in the particle:
\[ u_s = \frac{Q}{S}. \]  

(5)

**Table 2.** Results of measurements of the drag coefficient of the particle upon the gas injection from its surface.

| \( Q, \text{ m}^3/\text{s} \) | \( 0.350 \times 10^{-3} \) | \( 0.350 \times 10^{-3} \) | \( 0.525 \times 10^{-3} \) | \( 0.525 \times 10^{-3} \) |
|-------------------------------|------------------|------------------|------------------|------------------|
| \( u, \text{ m/s} \)           | 1.66             | 2.65             | 1.66             | 2.65             |
| \( \alpha, \text{ deg} \)     | 1.2              | 4.0              | 1.0              | 3.5              |
| \( C_x \)                     | 0.267            | 0.350            | 0.222            | 0.306            |
| \( u_s, \text{ m/s} \)        | 2.61             | 2.61             | 3.91             | 3.91             |
| \( \text{Re}_s \)             | \( 6.94 \times 10^3 \) | \( 6.94 \times 10^3 \) | \( 10.41 \times 10^3 \) | \( 10.41 \times 10^3 \) |

Dependencies of the drag coefficient \( C_x \) on the Reynolds number \( \text{Re}_0 \) upon varying the ratio of the gas injection rate and the velocity of the flow blowing around the particle are shown in Fig. 2.

**Figure.** 2. Dependences of the drag coefficient \( C_x \) on the Reynolds number \( \text{Re}_0 \): 1 – in the absence of the gas injection from the particle surface; 2 – upon the gas injection from the particle surface with a volumetric flow rate \( Q = 0.350 \times 10^{-3} \text{ m}^3/\text{s} \); 3 – upon the gas injection from the particle surface with a volumetric flow rate \( Q = 0.525 \times 10^{-3} \text{ m}^3/\text{s} \).

From the data presented, it follows that when the gas is injected from the particle surface in the examined range of the \( \text{Re}_0 \) and \( \text{Re}_s \) numbers, the drag coefficient decreases \((C_x < C_{xo})\). The difference between the values of \( C_{xo} \) and \( C_x \) increases with increasing the flow rate of the injected gas (the \( \text{Re}_s \) number) at the same blowing flow rate (the \( \text{Re}_0 \) number). This reduction of the drag coefficient upon
the gas injection from the particle surface is more pronounced with decreasing the velocity of the blowing flow.

4. Conclusion
A new technique for measuring the drag coefficient of spherical particle upon at condition the gas injection from its surface is presented.

- The drag coefficients of the particle upon the gas injection from its surface and in the absence of the gas injection are obtained.
- It is shown that the obtained drag coefficient (without the gas injection) in the examined range of the Reynolds numbers Re0 are consistent with the common dependence for the turbulent flow regime.
- It is shown that when the gas is injected from the particle surface in the examined range of the Reynolds numbers, the drag coefficient decreases by about 20%.

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