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An experimental study of the effect of particles on the shear stress in particulate turbulent pipe flow

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Abstract. Experimental data on the shear stress, exerted by a flowing mixture of solid particles in air, are presented. The data were obtained in a facility with a steel or vinyl test section. The Reynolds numbers were close to 10^5, thus the flow was turbulent. Several types of particles with different material properties were used. Low as well as intermediate-to-high values of the loading ratio were investigated. It was found that the reduction of the data with respect to the Gastershtadt coefficient K highlights certain trends of the flow and makes it possible to derive some general conclusions on the behaviour of the mixture.

Key words: gas–solid pipe flow, turbulence, loading ratio, shear stress, Gastershtadt coefficient.

1. INTRODUCTION

Pressure loss (pressure change) in gas–solid pipelines has been a subject of several investigations [1–5]. Several sets of experimental data have been published and relationships for the pressure drop have been formulated, which exhibit various degrees of accuracy in predicting data, different from the ones derived in [6]. Most of these relationships are for low to intermediate values of the loading ratio and utilize few types and sizes of particles.

The authors of [3], considering turbulent gas–solid flow in a horizontal pipe, revealed a dependence of the pressure drop for particle transport on the ratio of the densities of the solid and fluid phases of the flow. They explained this ratio as representing the mean velocity slip between the fluid and the solid material. The authors of [4] investigated a vertical upward gas–solid two-phase flow. They showed experimentally that the frictional pressure drop is an important component of the total pressure gradient in the riser of the vertical pneumatic conveying system and that at low gas velocities negative frictional pressure gradients occur.

Today a reliable metering of the flow rate of solids is of great importance for effective operation and control of gas–solid transport systems in industry. The authors of [5] experimentally examined the principle of measuring the pressure loss, experienced by a gas–solid flow in a straight section of piping in order to obtain the flow rates for a wide range of powders and granular materials. The results of [7] verified the possibility of widespread industrial application of the pressure drop metering devices.

The purpose of this study is to determine experimentally the effect of the solids loading on the total shear stress and the pressure drop, under steady-state turbulent flow conditions, utilizing several types of particles. The Reynolds number Re varied from 2×10^4 to 3×10^5, the pipeline inner diameter was in the range of 16–66 mm and the pipeline materials were stainless steel and vinyl. Experiments were conducted with the mass loading ratio m in the low range $(0 < m < 15)$ as well as in the intermediate-to-high range $(0 < m < 15)$.

2. EXPERIMENTAL FACILITY

The experiments were carried out in a horizontal two-phase system, a schematic diagram of which is shown in Fig. 1. The power to run the system was supplied by a blower of 3.2 kW. The maximum mass flow rate of air was 0.2 kg/s. An automatic control system determined the air flow through the system and kept the flow constant during the experiments. The air flow rate was measured by a Venturi flowmeter with an uncertainty less than 10%. The thermal controller maintained the desired level of air temperature at the inlet, which was in the range of 20–40 °C.

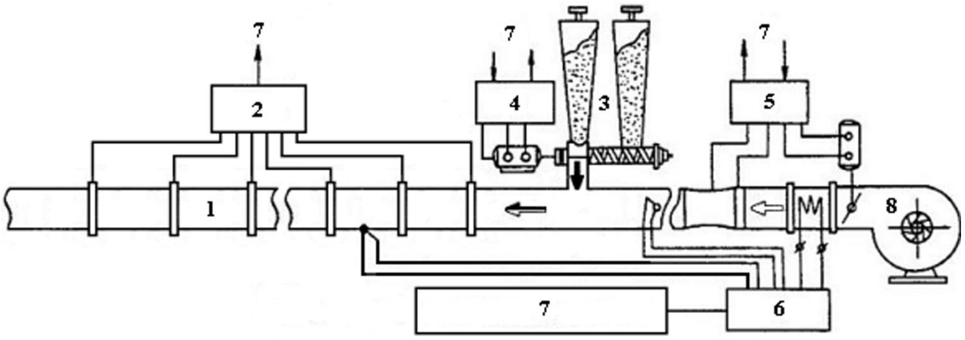


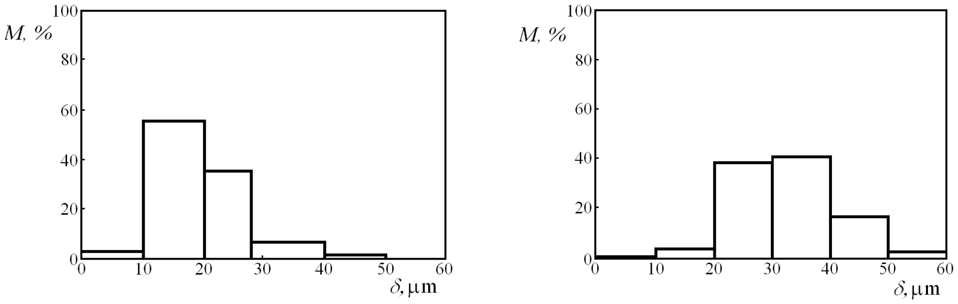
Fig. 1. Experimental set-up: 1 – test section; 2 – pressure converter; 3 – particle screw feeder; 4 – control unit of the particle screw feeder; 5 – flowmeter; 6 – thermocontroller; 7 – registering, processing and controlling system; 8 – blower.

Particles were introduced into the flow stream by a screw feeder, which was supplied with its own control unit. The test section was 4 m long and was made of stainless steel or vinyl. The test section itself consisted of 16 smaller pipe sections that were joined by flanges. A straight pipe section of 3 m before the test section assured uniform acceleration of the particles before they reached the test section. A series of sixteen pressure transducers recorded the pressure along the test section. At the end of the test section, a cyclone separator (not shown in Fig. 1) was used to separate the particles from air. The experimental facility was equipped with an automatic data acquisition system, which also helped to control the experiments and to keep the flow parameters at a steady-state level.

The pressure sampling was carried out along the whole length of the pipe test section at every 0.25 m (a total of sixteen transducers were used). Uncertainty of the pressure measurements was caused mainly by the procedural and instrumental errors. In order to reduce the overall uncertainty, the data array contained 50 000 measurements at each gage point for every experimental condition. Such data array allowed to obtain the overall uncertainty not exceeding 12%.

The powders of electrocorundum (Al_2O_3), silicon carbide (SiC) and bronze particles were used as the dispersed phase. Their material density ρ_s was 3970, 3200 and 8900 kg/m^3, respectively. The size of the particles δ varied in the range of 15–200 μm, which is the range of small but non-cohesive particles. The weight-average size of the particles was in the range of 16–88 μm. The particles were obtained from industrially used samples and were highly polydispersed. Thus in the case of electrocorundum with nominal sizes 16 and 32 μm, an analysis of the actual sizes of the particles used revealed histograms, shown in Fig. 2. The standard deviation of these distributions was approximately 30%.

The velocity slip for the given flow conditions varied in the range of 0–25% of the mean flow velocity depending on the particle size [8]. The transport velocity of the carrier fluid for the given range of the Reynolds number 2×10^4–3×10^5 was sufficient to keep the particles away from the bottom wall, thus excluding the precipitation process. Besides, the observed distribution of the particle mass concentration at the pipe exit is axisymmetric for these regimes [8].



(a) (b)

Fig. 2. The weight-average size distributions of electrocorundum particles of nominal sizes: (a) $\delta = 16$ μm; (b) $\delta = 32$ μm; M – the weight fraction.

3. EXPERIMENTAL RESULTS

From the measurements of the pressure gradient, one may easily obtain the shear stress and, hence, the friction coefficient of the two-phase mixture. From theoretical considerations on the behaviour of solid particles carried by a fluid in a pipe, one concludes that the best way to express the total shear stress τ_{m} is as the sum of the shear stress, induced by the flow of air alone, and the shear stress due to the presence of the particles [9–11]. Thus we used the following equation for modelling our data:

$$\tau_{\mathrm{m}} = \tau + \Delta\tau_{\mathrm{s}}, \tag{1}$$

where τ is the shear stress for $m = 0$ and $\Delta\tau_{\mathrm{s}}$ is the part of the shear stress due to the addition of the solid particles. In the case of dilute flows, where particle-to-particle interactions are not important, the excess shear due to the presence of particles is mainly due to two causes: a) the interaction of particles with the wall, and b) the interaction of particles with the fluid. Hence, the excess shear stress may be expressed in terms of two separate quantities: $\Delta\tau_{\mathrm{s}} = \Delta\tau_1 + \Delta\tau_2$. The last two terms are related to the particle–wall interactions $(\Delta\tau_1)$ and to the gas–particle interactions $(\Delta\tau_2)$. The component $\Delta\tau_1$ is a result of several complex forces, such as the Coulomb friction and particle–wall impacts. The part due to the gas–particle interactions $(\Delta\tau_2)$ also has a complex origin and includes the effects of the local modification of the gas velocity field, caused by the presence of particles, velocity slip between particles as well as by the gas and turbulence modulation by the particles [6,12–14].

Given the complex nature of $\Delta\tau_1$ and $\Delta\tau_2$, we did not model separately these two components of the excess shear stress $\Delta\tau_{\mathrm{s}}$. Thus, for the reduction of the experimental data, we assumed that $\Delta\tau_{\mathrm{s}}$ is proportional to the loading ratio m:

$$\Delta\tau_{\mathrm{s}} = Km\tau, \tag{2}$$

where K is the proportionality constant, which is sometimes referred to as the Gastershtadt coefficient [15]. Now Eq. (1) can be written as

$$\tau_{\mathrm{m}} = \tau(1 + Km). \tag{3}$$

In [9], K was given by the following expression:

$$K = \frac{2m}{c_{\mathrm{f}}}\frac{\sqrt{Dg}}{u}\frac{1-\xi}{1+\xi}, \tag{4}$$

where D is the pipe diameter, c_{f} is the friction coefficient at $m = 0$, ξ is the bouncing coefficient of the particles with the wall, u is the fluid velocity and g is the gravitational acceleration.

Equation (2) implies that the contribution of particles to the shear stress is proportional to the fluid stress τ and to the mass loading ratio m of the particles.

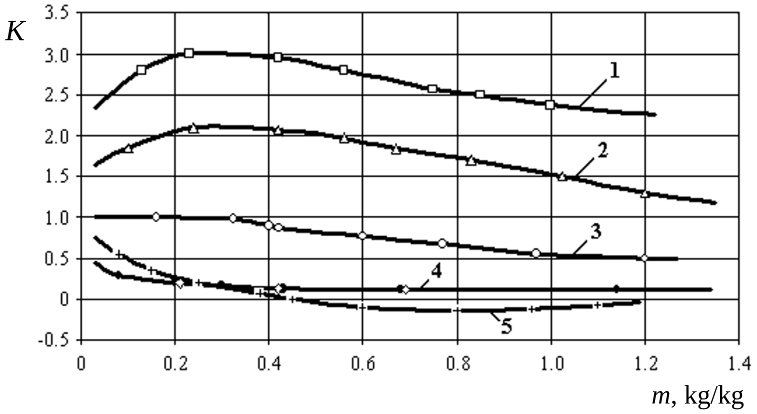


Fig. 3. The coefficient K vs the particle mass loading and the particle size for the stainless steel pipe by $Re = 6.2\times10^4$, $D = 32.7$ mm: 1 – Al_2O_3, $\delta = 88$ μm; 2 – Al_2O_3, $\delta = 70$ μm; 3 – SiC, $\delta =$ 55 μm; 4 – Al_2O_3 (●), $\delta = 32$ μm, SiC (◇), $\delta = 32$ μm; 5 – Al_2O_3, $\delta = 16$ μm.

Figure 3 shows the dependence of the coefficient K on the mass loading for very dilute flows, where m is less than 1.5. It is evident that in this case K depends on the mass loading as well as on the size of the particles. Smaller particles tend to have lower values of K, and the smallest ones even exhibit negative values; this implies that the total shear stress is reduced. We believe that this is due to the turbulence modulation in the gaseous phase, which is usually experienced in the fine particle range [13,14]. In terms of the two components of the excess shear stress $\Delta\tau$ we have a significant reduction of $\Delta\tau_2$, which counteracts any increase of the component $\Delta\tau_1$. This reduction is expected to persist only at small values of the loading ratio $(m < 3)$ even with fine particles. Figure 3 shows that in the case of the particles with $\delta = 55$ μm, K would become positive at values of the loading ratio higher than 1.2. This means that the gains of any turbulence reduction would not be sufficient to counteract the shear stress increase due to the other causes, such as particle–wall collisions, acceleration of particles and simple Coulomb friction due to particles.

It is also evident in Fig. 3 that the curves, corresponding to the larger particles (for which turbulence reduction is not expected), reach a maximum value and then level off. This is a manifestation of the fact that the marginal cost (in terms of the pressure drop) associated with the transport of solids is reduced with an increase of the solids loading.

At low values of the loading ratio, the coefficient K apparently varies with the loading ratio and may reach a maximum or a minimum value as Fig. 3 indicates. However, at high values of the loading ratio, we expect that equilibrium will be reached between the overall gas–particle–walls interactions and that K will approach a constant value. A series of experiments we performed with bronze particles at high values of m shows that K is almost constant over a very large range of loading ratios and gas Reynolds numbers. In this series of experiments we used three sizes of bronze particles (35, 45 and 67 μm) and two types of pipes made of stainless steel and vinyl. The results of these experiments are shown in Fig. 4 as the ratio τ_{m}/τ vs the mass loading. Despite some deviations from the norm, the data show a markedly linear trend, which implies that K is almost constant over a long range of the loading ratio m.

The function $K(m)$ was calculated from Fig. 4 and Eq. (3). The actual results for K are shown in Fig. 5, where it is observed that K is almost constant (equal

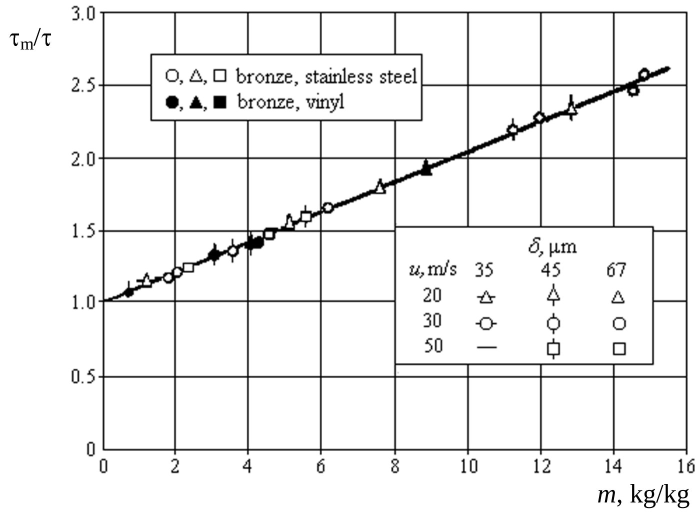


Fig. 4. The shear stress ratio vs mass loading for bronze particles.

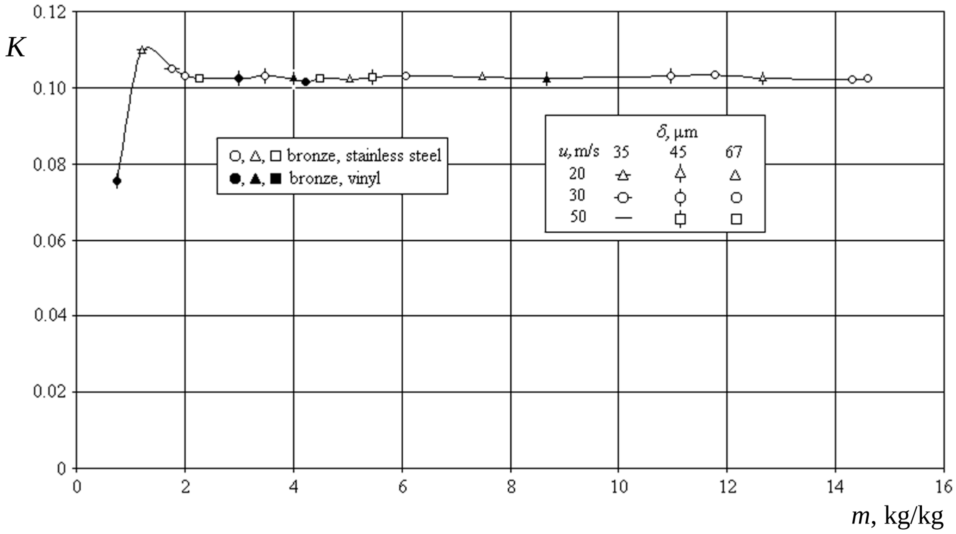


Fig. 5. The Gastershtadt coefficient vs the loading ratio for bronze particles.

to 0.102) in the range of $2 < m < 15,$ which covers the low and intermediate loadings. The uncertainty of data for K and $\tau_{\mathrm{m}}/\tau,$ presented in Figs. 3 to 5, is caused by the uncertainty of the pressure measurement and does not exceed 12%. It must be pointed out that in the dense range of solids transport $(m > 20)$ it is expected that the value of K will change, because different effects govern the flow and transport of solids.

4. CONCLUSIONS

Experiments, performed in an automated horizontal facility, show that the total shear stress is a sum of the stress at zero loading and of an excess stress, due to the presence of the particles. The excess shear stress of a gas–solids mixture is a linear function of the mass loading for a wide range of loadings. The constant of proportionality depends on the type of solids conveyed. At very low loadings, this constant K is a function of the loading. The experimental data indicate that K reaches maximum (for large particles, which contribute to the turbulence increase) or minimum (for small particles, where turbulence modulation may be expected) value and then levels off to a constant value. The value of K reaches a constant value at intermediate values of the loading ratio.

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Osakeste mõju nihkepingele tahkete osakestega õhu turbulentsel voolamisel kanalis. Eksperimentaalne uurimus

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ja Efstathios E. Michaelides

On kirjeldatud horisontaalse, turbulentse, tahkete osakestega koormatud õhu toruvooluse eksperimentaalset uurimist ja esitatud erinevate osakeste põhjustatud nihkepingete mõõtmise tulemusi. Voolusi uuriti nii osakeste madalate, keskmiste kui ka suurte masskontsentratsioonide korral. Leiti, et osakestest põhjustatud nihkepinge suurenemine on lineaarses sõltuvuses osakeste masskontsentratsioonist selle laiades piirides. Võrdelisuse teguri Gastershtadti koefitsiendi väärtus sõltub oluliselt osakeste tüübist.