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Experimental study of the effect of velocity slip and mass loading on the modification of grid-generated turbulence in gas–solid particles flows

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Abstract. Experimental data on the effects of the velocity slip and mass loading on a grid-generated turbulence in gas–solid particles flow are presented. Glass beads (700 μm) were used as the dispersed phase. Velocities of both phases were measured with a Laser Doppler Anemometer. Turbulence decay curves, obtained for different grids, show that particles enhance turbulence for small grids and attenuate it for the large ones. Turbulence enhancement and attenuation are intensified with the increase of the flow mass loading. The particles effect on turbulence changes from turbulence attenuation for a small velocity slip to its enhancement for a large velocity slip. A criterion for the evaluation of turbulence modification in gas–solid particles flow is proposed.

Key words: gas–solid particles flow, grid-generated turbulence, turbulence modification, mass loading ratio, velocity slip.

1. INTRODUCTION

The effect of solid particles on turbulence has been a prime issue of many experimental studies during last decades. New results about the dependence of turbulence on both the ratio between the particle size and the Euler turbulence length-scale δ/L_E and the particle Reynolds number Re_p were obtained in [1,2]. Later on, the dependence of the attenuation of the turbulent energy on the particle mass loading was established in [3]. The data were classified into two groups: the first group consisted of light particles with low Stokes numbers St_E, based on the Euler turbulence time scale T_E with a weak dependence of the turbulence attenuation on the mass loading; the second one consisted of heavy particles with more sharp dependence of the turbulence attenuation on the mass loading. However, the influence of particles on turbulence, depending on the Stokes number, is still an open issue. For instances, the authors of [4] found that the turbulence attenuation for a given mass loading depends weakly on the Stokes number; on the contrary, the authors of [3] found a considerable increase of the turbulence attenuation with the increase of St_{E}. Therefore experiments with various Reynolds and Stokes numbers of the particles would clarify the effect of particles on turbulence.

The grid-generated turbulence is an appropriate subject to study the effect of particles on the turbulence modification since, first, it is well studied theoretically and experimentally for the single-phase flow and, secondly, there are no complicating factors for analysis such as non-uniformity of the flow fields or the influence of the confining surfaces. Besides, it is easy to vary the Stokes number by changing only the grid parameters. However, experimental investigation of the grid-generated turbulence in gas–solid particles flows is complicated, first of all due to large transverse dimension of the flow that results in high mass flow of particles and also because of the difficulties in optical probing. Problems concerning entering of particles into the flow make the task even more complicated. Because of that, there is a lack of experimental studies concerning the grid-generated turbulence in two-phase flows. The papers [5–7] are among the few papers devoted the given problem. For example, while studying the effect of the air bubbles on the turbulence intensity behind a grid, the authors of [5] observed both attenuation and enhancement of the turbulence for a wide range of the energy spectrum of the liquid phase. The grid-generated turbulence in a water flow, loaded by 655 μm plastic or glass particles, was investigated in [6]. Here the mean flow velocity was 1 m/s and the Reynolds number Re_M, calculated for the grid mesh size M, was 15 600. A short section of the initial period of the turbulence decay for $15 < X/M < 33$, was studied (X is the streamwise coordinate counted down the stream behind the grid). It was found that the light plastic particles caused an increase of the longitudinal component of the turbulent energy, but heavy glass particles decreased the transversal component of the latter. It should be noted that experimental results on the effect of particles on turbulence in the water flow are hardly comparable with similar ones obtained for the air flow, because in case of the water flow the same values of the mass loading of the flow by the same particles can be obtained for the volume concentration of particles of 3 orders of magnitude higher than in air. As numerous investigations have shown, the character and the amount of change of the turbulence by particles in many respects depend on both the volume concentration and the mass loading. Unfortunately, no much attention has been paid to similar studies in gas–solid particles flows until now. As an exception, paper [7] can be mentioned, where the effect of 120 and 480 μm glass beads on the decay of the grid-generated turbulence in the downward air flow was studied. It was found that 120 μm particles with $Re_{\mathrm{p}} \approx 13$ decreased turbulence, whereas

480 μm particles with $Re_\mathrm{p} \approx 170$ increased it. However, these experiments were conducted for only one type of the grid. Thus the parameters of the initial turbulence were not varied and it was not possible to reveal their influence on the turbulence modification in the case of the two-phase flow.

Thus experimental investigations of the effect of parameters of the initial turbulence as well as of the velocity slip and flow mass loading on the turbulence of the gas phase of flow are needed. This study tries to fill partly this gap.

2. EXPERIMENTAL CONDITIONS

The experiments were carried out in a vertical two-phase open-loop wind channel with a closed test section described in detail in [8]. The instantaneous velocities of the tracer particles and particles of the dispersed phase were measured with a Laser Doppler Anemometer (LDA) [9]. Glass beads of the density $\rho_\mathrm{p} = 2500$ kg/m^3 with a diameter of $\delta = 700$ μm were used as the dispersed phase. A gravity acceleration device was used. This device allowed to obtain the required velocity slip for high values of the mass loading ratio of the flow. Three different grids were used (Table 1, where d is the diameter of the grid rods and S is the solidity of the grid).

The grid Reynolds number Re_M, which is calculated as

$$Re_M = \frac{uM}{\nu} \tag{1}$$

for the given mean gas flow velocity $u = 9.5$ m/s was 3040, 6333 and 10 133, respectively. Here ν is the kinematic viscosity of gas.

The investigation of the influence of the velocity slip on turbulence was carried out for the positive velocity slip, i.e. when particles lagged the gas. The velocity slip was set only by the preliminary acceleration of particles before their entering into the flow, without changing the parameters of the particles or of the initial single-phase flow.

The influence of the flow mass loading æ on turbulence was explored for the range of æ from 0 to 1 (kg dust)/(kg air). The mass flow of the dispersed phase was measured by the isokinetic sampling technique [10] and on-line monitored by the Laser Concentration Measurer [11].

Table 1. Parameters of the grids

M, mm	M/d	S
4.8	2.53	0.487
10	2.50	0.490
16	4.00	0.360

3. RESULTS

Figure 1 shows decay curves of the turbulence $u^2/u'^2_{\rm rms}$ ($u'_{\rm rms}$ is the root mean square value of the gas fluctuation velocity) behind different grids in the single- and two-phase flow for the mass loading of 0.14 (kg dust)/(kg air). The velocity slip $u_{\rm r} = u - u_{\rm s}$ was about 4 m/s ($u_{\rm s}$ is the mean particles velocity). As follows from Fig. 2, the pronounced turbulence enhancement by particles is observed for the grids $M = 4.8$ and 10 mm, while for the grid $M = 16$ mm the turbulence attenuation takes place. The character of the turbulence attenuation

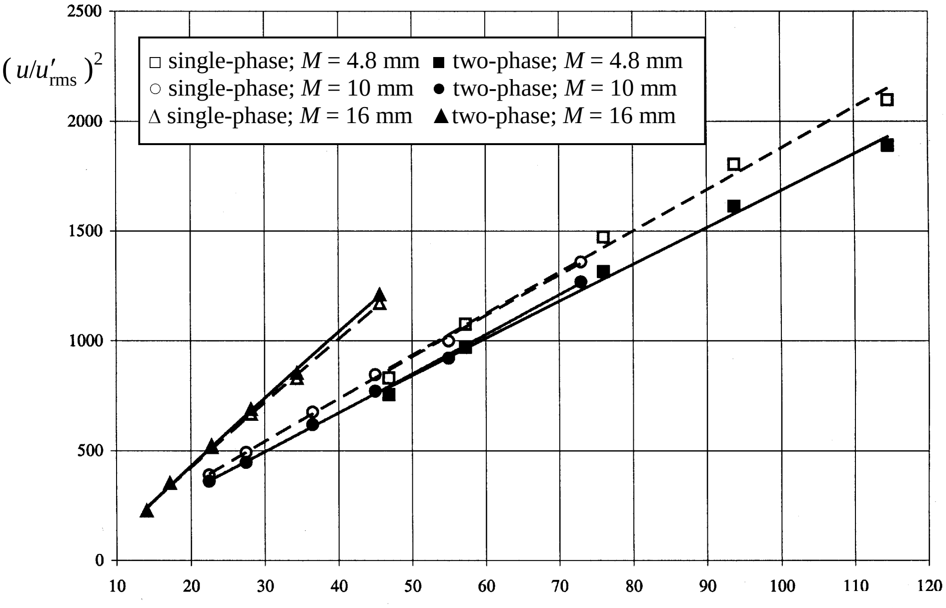

Fig. 1. Decay curves behind different grids.

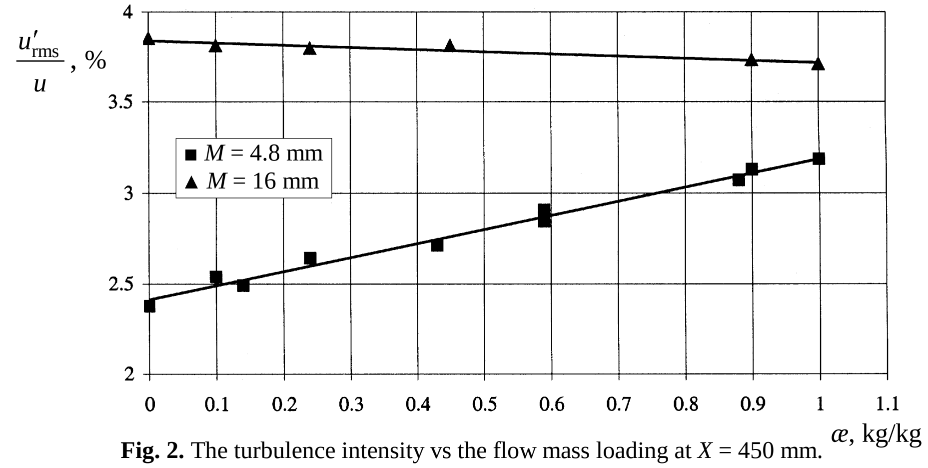

Fig. 2. The turbulence intensity vs the flow mass loading at X = 450 mm.

Table 2. Constants of the decay curves of different grids

M, mm	C	A
4.8; single-phase flow	20.09	2.62
4.8; two-phase flow	17.59	–0.01
10; single-phase flow	18.80	0.91
10; two-phase flow	18.0	3.15
16; single-phase flow	29.28	5.63
16; two-phase flow	30.57	6.04

behind the grids agrees with the well-known behaviour of the decay curves in grid-generated turbulent flows described in [12]:

$$\frac{u^2}{u'^2_{\mathrm{rms}}} = C\left(\frac{X}{M} - A\right), \tag{2}$$

where C and A are coefficients according to Table 2.

Experimental results (Fig. 2) show that increase in the mass loading of the flow results in the intensification of the additional turbulence generation for the grid $M = 4.8$ mm and in the attenuation of the turbulence for the grid $M = 16$ mm. As it can be seen from Fig. 2, the turbulence intensity depends linearly on the mass loading at least up to 1 (kg dust)/(kg air).

Most interesting are the results concerning the turbulence modification by particles with various velocity slip (Fig. 3). The influence of the velocity slip on turbulence is distinctly apparent in case of the grid $M = 16$ mm. The turbulence attenuation is observed for this grid for small velocity slip, while for large slip (larger than 3.5 m/s) the character of the particles effect changes to the opposite, i.e. the turbulence enhancement takes place. Thus for the given experimental conditions for $M = 16$ mm, the velocity slip determines the character of the particles effect. The turbulence enhancement by particles with larger values of the velocity slip was observed also for the grids $M = 4.8$ and 10 mm.

The turbulence structure of a single-phase flow behind the grid is determined by such flow parameters as the mean flow velocity u, the grid mesh size M and the ratio M/d [12]. The character of the particles effect on turbulence of the gas phase in the two-phase flow depends both on the turbulence parameters of the initial single-phase and the parameters of the dispersed phase, such as diameter δ, the material density ρ_{p}, the flow mass loading *æ*, the particle Reynolds number Re_{p} and the Stokes number St_{E}. In order to analyse the experimental results, the experimental parameters of the single- and two-phase flows at the location $X/M = 50$ along the flow axis are presented in Table 3. In Table 3 the following notations are used:

the Euler integral turbulence time scale $T_{\mathrm{E}} = \dfrac{L_{\mathrm{E}}}{u}$, (3)

the Kolmogorov turbulence time scale $t_{\mathrm{K}} = \left(\dfrac{\nu^3}{\varepsilon}\right)^{1/4}$, (4)

η_K is the Kolmogorov turbulence length scale, k is the turbulence kinetic energy and ε is the dissipation rate of the turbulence kinetic energy.

Table 4 shows the parameters of the dispersed phase. The change of the turbulence intensity by the particles Ch is calculated according to [1]:

$$Ch = \frac{(\sigma_{\mathrm{TP}} - \sigma_{\mathrm{F}})}{\sigma_{\mathrm{F}}} \times 100, \tag{5}$$

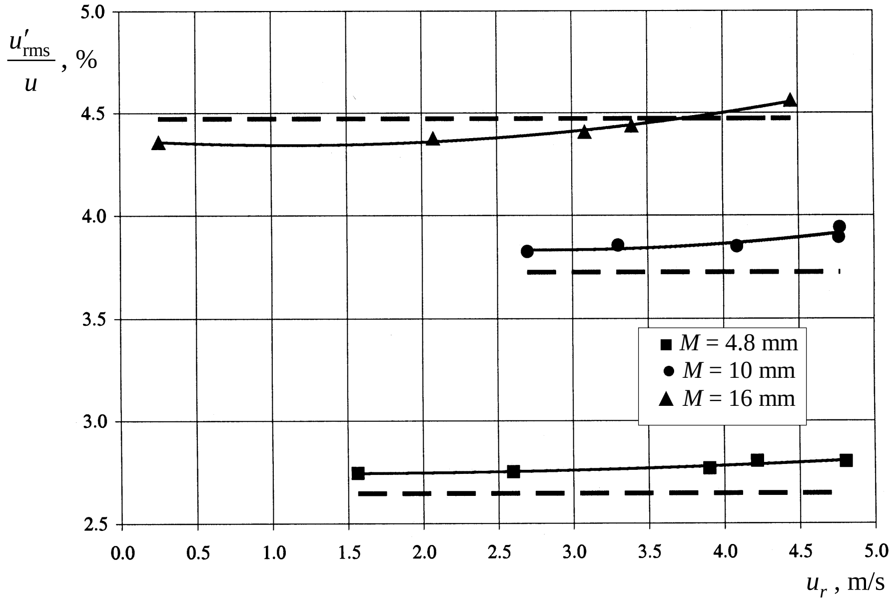

Fig. 3. The turbulence intensity vs the velocity slip at the location X = 365 mm. Heavy dash lines denote the turbulence intensity for different grids in the single-phase flow.

Table 3. Experimental parameters of the single- and two-phase (bold) flows at the location X/M = 50

Parameter	M, mm		
	4.8	10	16
T_E, s	2.51×10^{-2}	5.11×10^{-2}	7.47×10^{-2}
	2.53×10^{-2}	**5.03×10^{-2}**	**7.40×10^{-2}**
t_K, s	1.61×10^{-3}	2.28×10^{-3}	3.28×10^{-3}
	1.54×10^{-3}	**2.18×10^{-3}**	**3.32×10^{-3}**
η_K, m	1.55×10^{-4}	1.85×10^{-4}	2.22×10^{-4}
	1.52×10^{-4}	**1.81×10^{-4}**	**2.23×10^{-4}**
L_E, m	9.54×10^{-3}	1.96×10^{-2}	2.41×10^{-2}
	1.01×10^{-2}	**2.01×10^{-2}**	**2.35×10^{-2}**
k, m^2/s^2	1.45×10^{-1}	1.47×10^{-1}	1.04×10^{-1}
	1.61×10^{-1}	**1.59×10^{-1}**	**1.01×10^{-1}**
ε, m^2/s^3	5.786	2.876	1.394
	6.364	**3.162**	**1.360**

where σ_{TP} and σ_{F} are the turbulence intensities of the two-phase and single-phase flow, respectively; σ is calculated from Eq. (2) as follows:

$$\sigma = \frac{u'_{\mathrm{rms}}}{u}. \tag{6}$$

The volume concentration of the dispersed phase is calculated as

$$\beta = \frac{\rho æ u}{\rho_{\mathrm{p}} u_{\mathrm{s}}}, \tag{7}$$

where ρ is the material density of gas.

Re_{p} is the particle Reynolds number:

$$Re_{\mathrm{p}} = \frac{u_{\mathrm{r}}\delta}{\nu}, \tag{8}$$

τ_{p} is the particle response time and St_{K} is the Stokes number based on the Kolmogorov turbulence time scale t_{K}. The ratio of the interparticle distance λ and the particle diameter δ is determined according to [13] as

$$\frac{\lambda}{\delta} = \left(\frac{\pi}{6\beta}\right)^{1/3} - 1. \tag{9}$$

As it can be seen from Table 4, the diameter of the particles used in experiments is substantially smaller than the energy-containing eddies $(\delta/L_{\mathrm{E}} < 0.08)$. Therefore, according to [1], only the turbulence attenuation should take place. However, the experimental data do show both turbulence attenuation and enhancement. At the same time, the increasing of the turbulence attenuation for $M = 16$ mm or reducing of the turbulence enhancement for $M = 4.8$ and 10 mm

Table 4. The parameters of the dispersed phase

Parameter	M, mm		
	4.8	10	16
Ch, %	5.31	4.05	–1.70
$æ$, kg/kg	1.4×10^{-1}	1.4×10^{-1}	1.4×10^{-1}
β	1.35×10^{-4}	1.19×10^{-4}	1.15×10^{-4}
u_{r}, m/s	4.4	3.7	3.5
Re_{p}	2.0533×10^{2}	1.7267×10^{2}	1.6333×10^{2}
τ_{p}, s	3.76	3.76	3.76
St_{K}	2.45×10^{3}	1.73×10	1.13×10^{3}
St_{E}	1.49×10^{2}	7.48×10^{1}	5.08×10^{1}
λ/δ	1.472×10^{1}	1.541×10^{1}	1.559×10^{1}
δ/η_{K},	4.50	3.78	3.16
δ/L_{E}	7.34×10^{-2}	3.57×10^{-2}	2.90×10^{-2}

that were observed in experiments, are in agreement with the general concept of the turbulence attenuation by the particles with decreasing ratio of δ/L_E.

Let us analyse the experimental results using the diagram presented in Fig. 4 [14], which exhibits the domains of the particles effect on the turbulence modification depending on the interparticle distance, related to λ/δ as well as to the Stokes numbers St_E and St_K. The shaded area in the given diagram corresponds to the given experimental flow conditions and shows the turbulence enhancement by particles that should occur.

Another criterion of the particles effect on turbulence, suggested in [15], is the particle Reynolds number Re_p, which determines the velocity slip. Figure 5 shows the dependence of the turbulence on Re_p. This plot also demonstrates that the turbulence attenuation takes place up to $Re_p \approx 175$, and turbulence is enhanced for $Re_p > 175$.

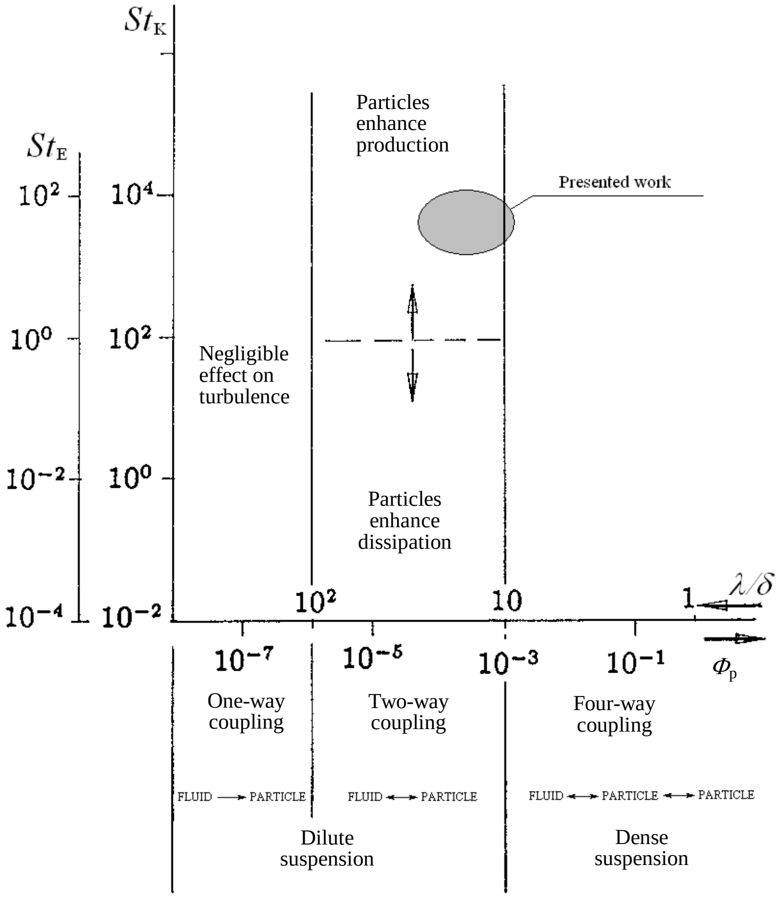

Fig. 4. The map of the flow regimes in particle-laden flows [14]; Φ_p is the volume fraction of particles: $\Phi_p = NV_p/V$ (N is the number of particles, V_p is volume of a particle and V is the volume occupied by particles and fluid).

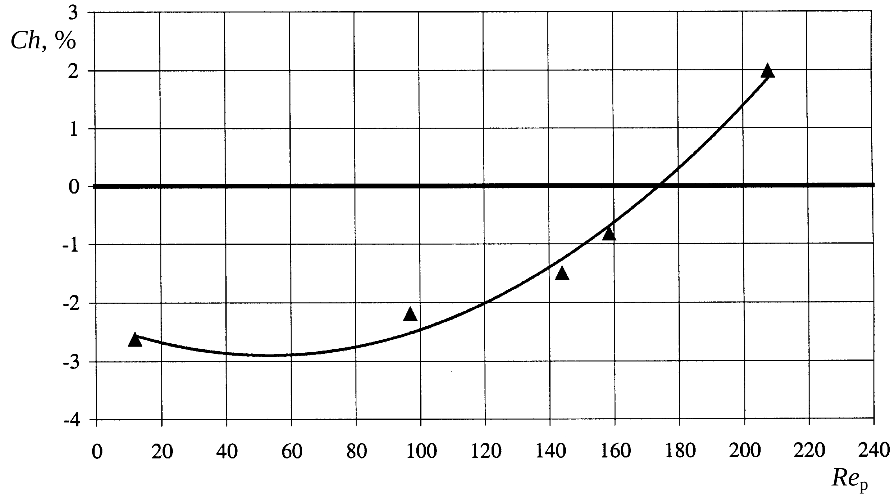

Fig. 5. The change of the turbulence intensity by particles vs Re_p for the grid $M = 16$ mm at the location $X = 365$ mm.

The criterion Re_p reflects the influence of the averaged velocities of the gas and particles and does not consider the turbulence parameters of the initial single-phase flow. Therefore, it is necessary to choose a criterion that would consider turbulence of the initial single-phase flow. The turbulence Reynolds number Re_L, determined by the Euler turbulence length-scale L_E and the fluctuating velocity of gas u'_{rms} as

$$Re_L = \frac{u'_{rms} L_E}{\nu}, \tag{10}$$

can be accepted as such a criterion.

Let us clarify in what way the conditions of turbulence of the initial single-phase flow, which is characterized by Re_L, affect the particles influence on turbulence in the two-phase flow. It is evident that the portion of energy, supplemented by particles owing to the shedding of vortices, decreases with the increase of the turbulent energy of the initial single-phase flow. At the same time, according to [1], the particles effect moves towards the turbulence attenuation with the growth of the eddy size L_E of the initial single-phase flow. This implies that the particles effect Ch is in inverse proportion to Re_L that was verified by experimental data (Fig. 6).

It seems logical to unify both criteria, Re_p and Re_L, into a single generalizing criterion Re_p/Re_L. This approach is a development of the Crowe's criterion [1], since the ratio $Re_p/Re_L = (\delta/L_E)\cdot(|u-u_s|/u'_{rms})$ considers the velocity characteristics of gas and particles in addition to Crowe's parameter δ/L_E. Thus the introduced criterion enables one to consider the combined influence of the parameters of the dispersed phase and of the initial single-phase flow on the turbulence of the carrier phase of the two-phase flow. Based on the processing of the experimental data, obtained with the fixed mass loading for different grids at various velocity slips in different cross-sections of the flow, the dependence of the change of the turbulence intensity on the ratio Re_p/Re_L is obtained (Fig. 7). As Fig. 7 shows, all experimental data are fitted by the curve, which shows the point of transition from the turbulence attenuation to its enhancement at $Re_p/Re_L \approx 0.4$. Based on linear dependence of the change of the turbulence intensity by particles on the mass loading, stretch or shrink of this curve in vertical direction, depending on the flow mass loading, can be expected.

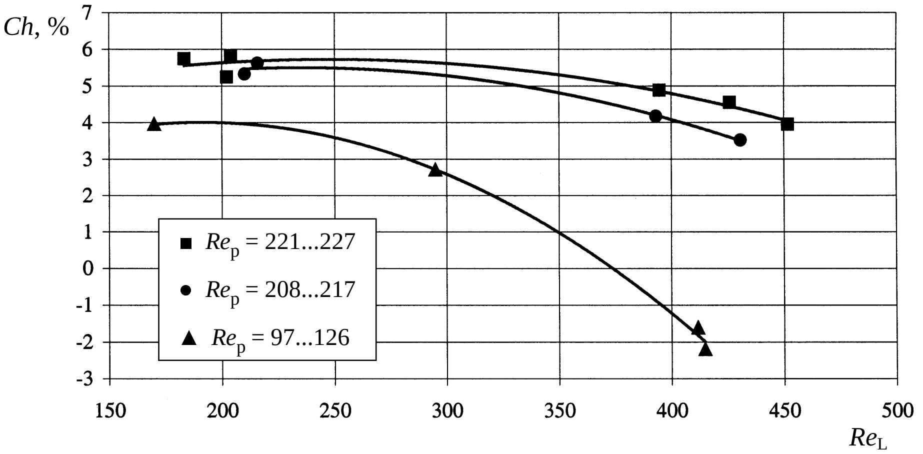

Fig. 6. The change of the turbulence intensity by particles vs Re_L for different values of Re_p.

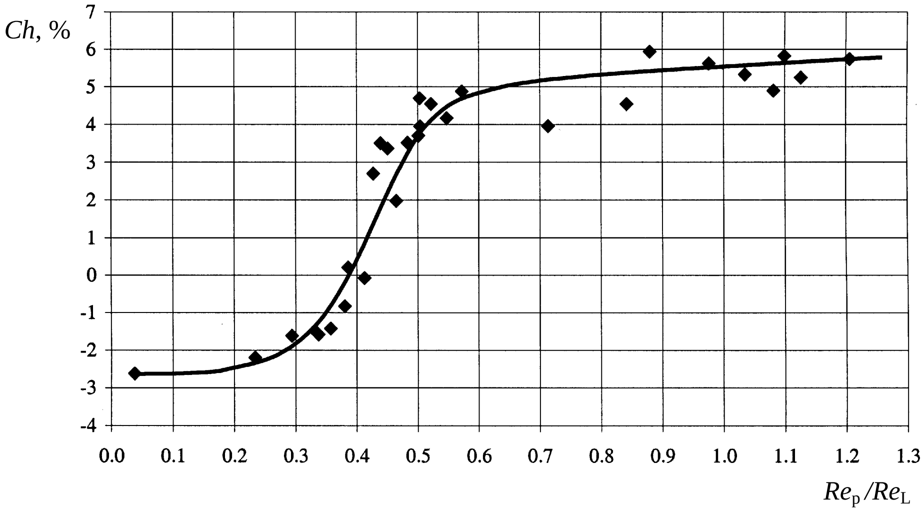

Fig. 7. The change of the turbulence intensity by particles vs Re_p/Re_L for the flow mass loading *æ* = 0.14 (kg dust)/(kg air).

4. CONCLUSIONS

Experimental investigations of the effect of the velocity slip and of the mass loading on the grid-generated turbulence in a gas–solid particles flow have been carried out. The velocity slip was achieved by preliminary acceleration of particles before their entering the flow, when the parameters of the gas and dispersed phases were invariable. The obtained results allow to draw the following conclusions:

- the 700 μm glass beads may attenuate or enhance the turbulence, depending on the parameters of turbulence of the initial single-phase flow;
- the velocity slip determines the particles effect on turbulence for the grid $M = 16$ mm for the given experimental conditions; the turbulence attenuation is observed for small velocity slips, whereas enhancement takes place for the velocity slips larger than 3.5 m/s;
- the ratio $Re_{\mathrm{p}} / Re_{\mathrm{L}}$ is proposed as the criterion for considering the combined influence of the parameters of the dispersed phase and the initial single-phase flow on the turbulence of the carrier phase of the two-phase flow;
- $Re_{\mathrm{p}} / Re_{\mathrm{L}} \approx 0.4$ is the critical value for the given experimental conditions that determines the influence of particles on turbulence; at $Re_{\mathrm{p}} / Re_{\mathrm{L}} < 0.4$ the turbulent energy is attenuated and at $Re_{\mathrm{p}} / Re_{\mathrm{L}} > 0.4$ it is enhanced;
- the particles effect on turbulence depends linearly on the mass loading up to the loading of 1 (kg dust)/(kg air).

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Tahkefaasi kiirusliku nihke ja masskoormatuse mõju hindamine võreturbulentsi modifitseerumisele dispersses vooluses

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Eksperimentide läbiviimisel kasutati dispersse faasi moodustamiseks sfäärilisi klaasosakesi suurusega 700 µm, gaasi ja tahkete osakeste kiirusi mõõdeti laser-dopplermeetodiga. Turbulentsi sumbumiskõverad fikseeriti ruudukujuliste akendega võre taga, kusjuures võreakna suurused olid 4,8, 10,0 ja 16,0 mm. Nagu katsed näitasid, sumbus turbulents väikeste (4,8 ja 10,0 mm) võreakende puhul aeglasemalt kui samade parameetritega gaasivooluse puhul. See tõendab turbulentsi täiendavat genereerimist tahkete osakeste poolt. Samas põhjustasid osakesed turbulentsi sumbumist suure (16,0 mm) võreakna puhul. Dispersse vooluse masskoormatuse suurendamisel võimendus osakeste mõju vooluse võreturbulentsile mõlemal juhul. Faasidevahelise kiirusliku nihke mõju uurimisel dispersse vooluse turbulentsile nihkekiiruste vahemikus 0–5 m/s täheldati nii dispersse vooluse turbulentsi sumbumist kui ka genereerumist. Eksperimentaalsete andmete baasil määrati kriteriaalne parameeter, mis võimaldab arvestada dispersse faasi ja ühefaasilise lähtevooluse parameetrite mõju dispersse vooluse turbulentsile.