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EXPERIMENTAL INVESTIGATION OF TURBULENCE MODULATION BY ROUGH SOLID PARTICLES IN A GRID-GENERATED FLOW

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Abstract. Experimental results relating to the modulation of grid-generated turbulence by rough particles (glass beads of the size 700 μm) in vertical downward flow are presented. Two grids with mesh sizes of 4.8 and 10 mm generated isotropic turbulence. The grid Reynolds numbers were about 3000 and 6300, and the particle Reynolds number was about 80. Histograms of the particle velocity, distributions of the turbulence intensity along the axis of flow, and spectral density of the turbulent energy of flow in different cross-sections obtained by LDA measurements are presented. It was found that the presence of rough particles leads to the attenuation of the turbulence intensity of the flow and to the reduction of the energy at high frequencies.

Key words: vertical two-phase flow, grid-generated turbulence, turbulence modulation, decay curves, energy spectra.

1. INTRODUCTION

Experimental investigations of the particle influence on the turbulence of the carrier flow for various types of flows – in pipes and channels, jets and wakes, and in the flows with artificially generated turbulence – have revealed three effects: attenuation of the turbulence, its generation, and also negligible influence of the particles on the turbulence. This phenomenon is not well understood due to a variety of parameters influencing it. Moreover, the accuracy of the results obtained by different experimental investigations has a great impact on the reliability of the models used to predict turbulence modification in a two-phase flow.

Different approaches have been used to explain the influence of the particles on the turbulent structure of two-phase flows. Gore and Crowe [1] have analysed the dependence of the turbulence modulation on the ratio of the particle size δ to the integral turbulence length of the flow, L_E (δ/L_E). Their analysis showed that particles attenuate occurrence of the turbulence if this ratio is below 0.1 and augment the turbulence when the ratio is over 0.1. Later, Gore and Crowe [2] suggested to consider the influence of other parameters on the turbulence modulation as well: the ratio of the density of the particle material and gas (ρ_p/ρ), the Reynolds numbers of the flow (Re) and the particles (Re_p), the relative turbulence intensity, and the volume concentration β.

In the review by Hetsroni [3], the turbulence attenuation/augmentation is determined by a single criterion, namely the particle Reynolds number Re_p, calculated by means of the velocity slip between the gas and the particles. Hetsroni [3] has stated that for $Re_\mathrm{p} > 400$, wake effects become predominant resulting in the enhancement of the turbulence production and augmentation.

Snyder and Lumley [4] were the first to investigate experimentally the turbulent diffusion of particles of various physical density in a single-phase turbulent grid-generated flow. Using an optical measurement technique, they obtained the autocorrelation functions of the velocity fluctuations for various particles (light and heavy), the mean-square displacement of the particles, and also the decay curves along the flow axis. Unfortunately, the authors did not investigate the straight influence of the particles on the modulation of the turbulence decay behind the grid.

Schreck and Kleis [5] studied experimentally the mechanism of the turbulence decay behind the grid in a water stream using two types of particles, plastic and glass beads with mass-average diameter of about 0.65 mm. In these experiments the mean velocity of the water flow U was 1 m/s and the grid Reynolds number Re_M was 1.56×10^4 for the grid size of 17.8 mm. Results of this investigation have revealed the turbulence attenuation in water for both light (plastic) and heavy (glass) particles for various volumes of the solid phase (from 0.4 to 1.5%). Besides, the spectral energy density depended on the velocity component of the spectrum. Matching their results with a single-phase flow, in [5] an augmentation of the energy at high wave numbers for the streamwise velocity component was established. For the transversal velocity component as well as for the total turbulence energy of the primary flow, calculated as $E = E_u + 2E_v$ (here E_u and E_v are the energies of the streamwise and transversal components of the velocity fluctuations, respectively), a reduction of the turbulence energy for both types of the particles was observed.

The paper by Lance and Bataille [6] deals with the turbulence modulation of a water flow behind the grid by air bubbles. Comparing the results with a single-phase flow it was found that the bubbles fed up the water with the turbulent energy at low frequencies and withdraw the turbulence energy at the high frequency region.

The lack of experimental results about the influence of solid particles on the turbulent structure of the air flow behind the grid prompted to perform the present investigation.

2. EXPERIMENT AND DATA PROCESSING

The goal of the experiments was to study the influence of rough solid particles on the grid-generated turbulence. In order to get rid of the asymmetry of the two-phase horizontal flow loaded by inertial particles, experiments were carried out in a vertical downward flow (Fig. 1). In the case of the vertical steady flow, the velocity slip between the carrier phase and the particles equals to the terminal velocity of the particles. A developed two-phase flow can be obtained in a wide long channel with the length exceeding for 100 times the channel width. Thus, in our case the channel length should be about 20 m that is not feasible to mount. Therefore the particles were beforehand accelerated up to the desired velocity in a specially constructed particle feeder/accelerator device 8 to obtain initially negative velocity slip (the particles move ahead of the flow). With this device, which was installed at the flow intake 1 in front of the grid 4, the particles were brought into the main stream.

The experiments were carried out in a disconnected vertical two-phase wind channel with a closed test section 5 of square cross-section 200 × 200 mm, two meters long. By a suction fan, the air flew in the downward direction with the mean velocity of 9.5 m/s. The dispersed phase was modelled by rough glass particles with the mass-averaged size of 700 μm while the carrier gas-phase flow was modelled by fine Titanium dioxide TiO_2 particles with the mass-average size of 2 μm. The particles of both sizes were separated from the flow in a diffuser and conveyed then by pneumatic transport into the receiving bin 9.

Different levels of turbulence were generated by two different plane grids with the mesh sizes of 4.8 and 10 mm, respectively. High initial level of the turbulence intensity of the primary flow, about 3.5% in front of the grid, was partly caused by the presence of the particle feeder at the intake. The grid-generated turbulence decayed downstream, approaching its initial level in front of the grid.

A forward-scattering LDA was used for the measurement of the instantaneous velocities of the gas and particles [7,8]. The velocity of the gas was distinguished from the particle velocity by means of the amplitude discrimination of signals from the TiO_2 trace-particles and glass beads. The distributions of the streamwise velocity components of the gas and particles, the rms velocity, and the decay curves along the axis of the flow in various cross-sections downstream together with the energy spectra for the streamwise component of fluctuating velocity at various points behind the grid, were obtained by means of processing of the measured instantaneous velocities of both phases.

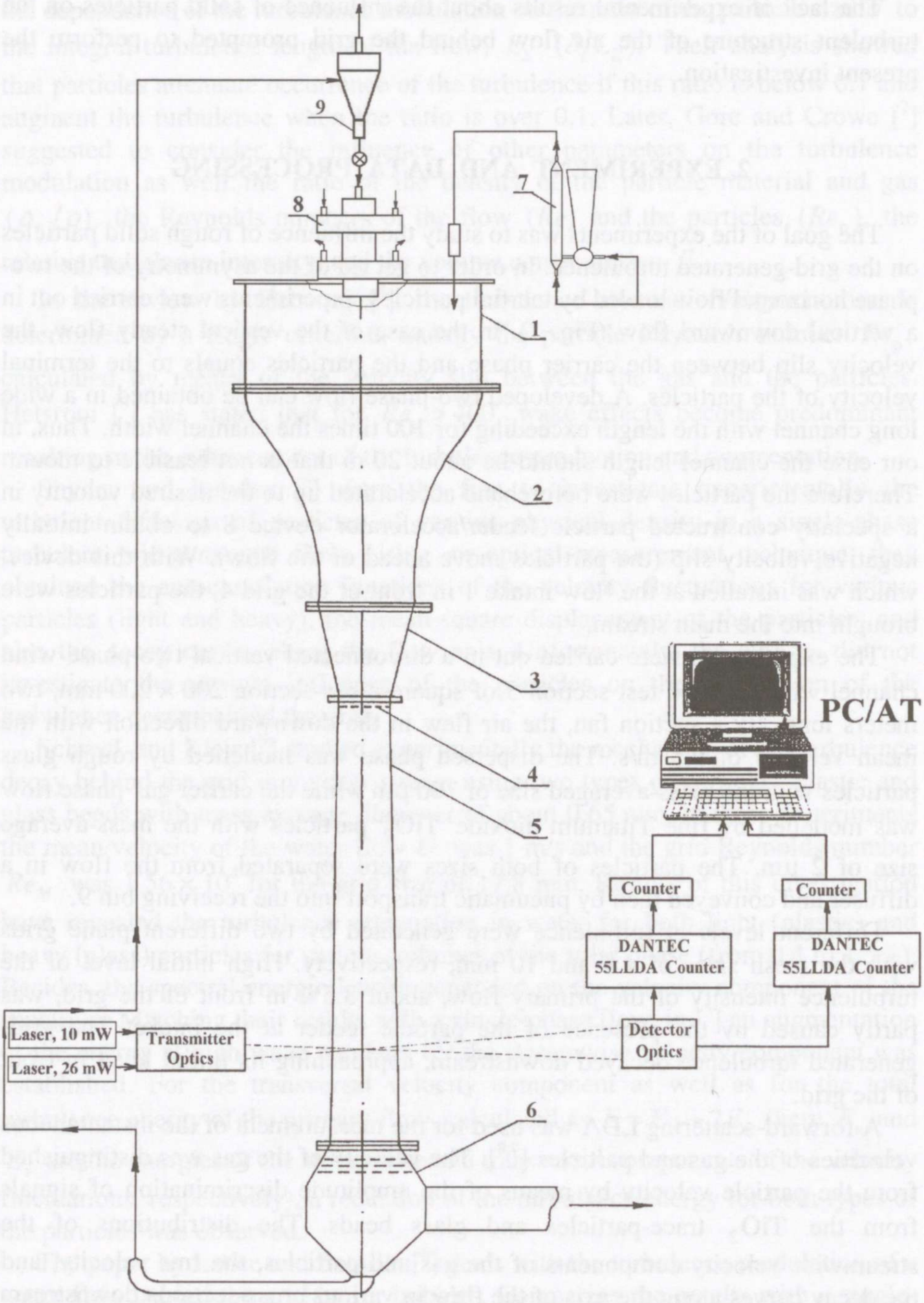

Fig. 1. Experimental set-up: 1 – intake; 2 – contractor; 3 – passage from round to square cross-section; 4 – turbulence generating grid; 5 – test section; 6 – diffuser; 7 – seeding generator; 8 – particle feeder/accelerator; 9 – receiving bin.

To obtain the data for the calculations of the power spectra of the velocity fluctuations of the carrier gas flow, 15 series of measurements were carried out with 2000 values of the instantaneous velocity. The average registration time for each series was about 0.3 s, i.e., the average frequency of the data rate was about 6.6 kHz. The initial assembly of the instantaneous velocities included 30 000 values with the time interval of 150 μs between each record. Each series of the instantaneous velocities was then filtered by the amplitude and time discrimination following the 3σ rule.

The power spectra of the velocity fluctuation was estimated by means of the Walch periodogram technique and with the help of rectangular windows using Marple's procedure for the length of 2048 values with overlapping of 1024 values of the data range [7,8].

Thus each series of the data allowed to calculate about 6 evaluations of the spectra during the time interval of 0.1 s which was appreciably larger than the time scale of the flow (0.02 s). From the initial assembly of 30 000 samples it was possible to obtain about 90 independent evaluations of the real spectrum.

The standard deviation for the profiles of the average velocity of the carrier gas flow was less than 0.5% and for the rms velocity less than 6%.

The mass flow of the dispersed phase was measured with the help of the isokinetic method [9]. The profile of the mass flow across the channel was measured simultaneously with 10 isokinetic tubes. For the measured mass flow and velocities of both phases, the profiles of the mass loading were calculated for every test series. The particle concentration $æ$ did not exceed 0.1 (kg dust)/(kg air) and was mostly about 0.05. The mass loading had almost uniform distribution across the channel. The upper limit of the mass loading was conditioned by the output of a circuit for recovering of the dispersed phase.

3. RESULTS AND DISCUSSION

Between the relevant parameters the following relationships are valid:

$$Re_{\mathrm{p}} = \delta v_{\mathrm{term}} / \nu, \tag{1}$$

$$t_{\mathrm{p}} = \delta^2 \rho_{\mathrm{p}} / 18 \rho \nu, \tag{2}$$

$$St_{\mathrm{K}} = t_{\mathrm{p}} / t_{\mathrm{K}}, \tag{3}$$

$$St_{\mathrm{E}} = t_{\mathrm{p}} / T_{\mathrm{E}}, \tag{4}$$

$$t_{\mathrm{K}} = (\nu^3 / \varepsilon)^{1/4}, \tag{5}$$

$$T_{\mathrm{E}} = L_{\mathrm{E}} / U, \tag{6}$$

where v_{term} is the particle terminal velocity, t_p is the particle response time, ν is the kinematic viscosity of the gas, St_K and St_E are the Stokes numbers in the Kolmogorov (t_K) and Euler (t_E) turbulence time scales, respectively, U is the average flow velocity, and ε is the dissipation rate of the turbulence kinetic energy.

Characteristics of the particles are shown in Table 1 were η_K and L_E are the Kolmogorov and the integral turbulence scale, respectively. The inter-particle spacing is calculated, according to [10], with the help of the particle size and the particle volume β as

$$\lambda = (\sqrt[3]{\pi / 6\beta} - 1)\,\delta, \tag{7}$$

and the smallest Kolmogorov turbulence scale is

$$\eta_K = \sqrt[4]{\nu^3 / \varepsilon}. \tag{8}$$

Table 1. Characteristics of the particles

Characteristic	Mesh size of the grid M, mm	
	4.8	10
Size δ, μm	700	
Density ρ_p, kg/m^3	2500	
Terminal velocity v_{term}, m/s	5.761302	
Concentration $æ$, kg/kg	0.05	
Volume β	3.1×10^{-5}	
Velocity slip U–U_p, m/s	1.5	2
Reynolds number Re_p	70	93
Response time t_p, s	4.5	
Stokes number St_K	5.48×10^3	3.76×10^3
Stokes number St_E	2.47×10^2	1.34×10^2
Inter-particle spacing λ, m	8.26×10^{-2}	8.26×10^{-2}
λ / δ	118	
δ / η_K	6.31	5.22
δ / L_E	6.22×10^{-2}	3.58×10^{-2}

Measurements were made in various cross-sections of the channel behind the grid at the distances 126, 191, 251, 383, 503, 692, and 1264 mm. The histograms of the particle streamwise velocity component in the cross-section at the distance $X = 191$ mm for both mesh sizes M of the grid are plotted in Figs. 2 and 3, respectively. The figures show also the function $N_\Sigma(U_p)$, the percentage of the particles with a velocity less or equal to U_p. In the absence of the turbulence generating grid, the particle feeder/accelerator gave the particles large negative velocity slip roughly equal to the terminal velocity (about 5 m/s). The measurements showed that the situation was different in the presence of the grid. There were only 35% of the particles in case of the grid of 4.8 mm (Fig. 2) and only 40% in case of the grid of 10 mm (Fig. 3) whose velocity exceeded the mean velocity of the gas (9.5 m/s) and only a small amount of the particles (roughly 15%) moved with the velocity slip larger than 3 m/s. That can be

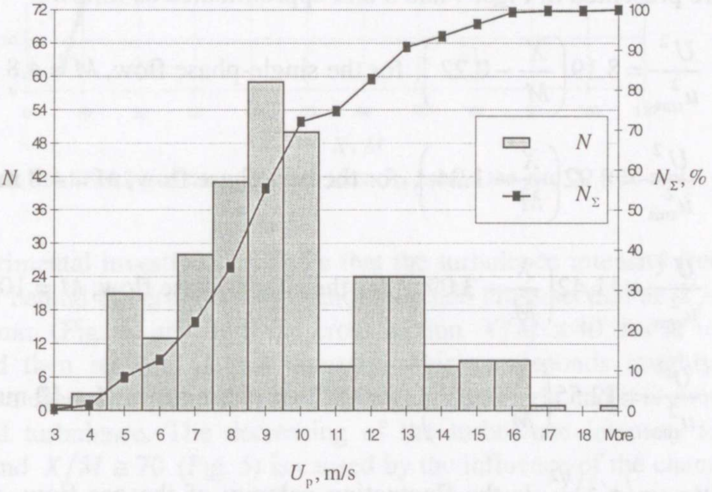

Fig. 2. Histogram of the streamwise velocity component of the particles on the flow axis (N in number of the particles) and the function $N_\Sigma(U_p)$ at $X = 191$ mm, grid size $M = 4.8$ mm.

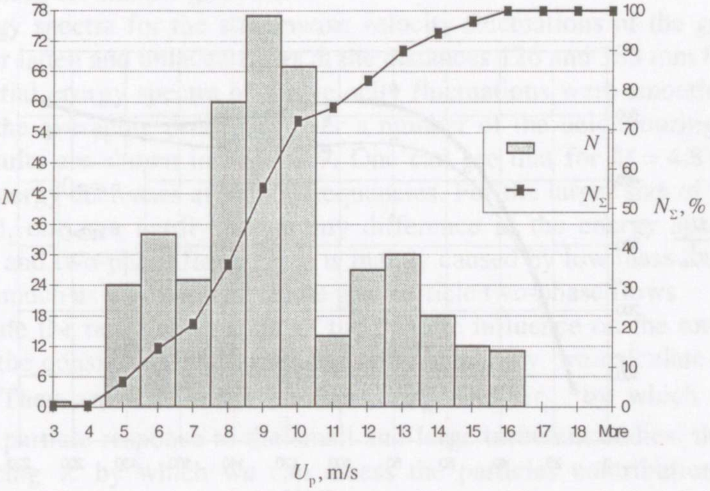

Fig. 3. Histogram of the streamwise velocity component of the particles on the flow axis and the function $N_\Sigma(U_p)$ at $X = 191$ mm, grid size $M = 10$ mm.

explained by the saltation motion of particles in the feeder/accelerator, i.e., by very intensive collisions of the particles with the walls, which causes a non-negligible transverse velocity component at the exit from the device. Besides, the particle size distribution causes a scatter of the velocities due to different particle inertia and the particles may collide with the grid rods and thus, rebound in arbitrary directions, partly redistribute their momentum in the transverse direction. The influence of the last factor becomes stronger when the grid size decreases.

The decay curves along the channel behind the grid for the laden and unladen flows are presented in Figs. 4 and 5 and approximated as follows:

$$\frac{U^2}{u_{\text{rms}}^2} = 8.19\left(\frac{X}{M} - 0.22\right), \text{ for the single-phase flow, } M = 4.8 \text{ mm}, \tag{9}$$

$$\frac{U^2}{u_{\text{rms}}^2} = 8.92\left(\frac{X}{M} - 1.24\right), \text{ for the two-phase flow, } M = 4.8 \text{ mm}, \tag{10}$$

$$\frac{U^2}{u_{\text{rms}}^2} = 11.42\left(\frac{X}{M} - 3.09\right), \text{ for the single-phase flow, } M = 10 \text{ mm}, \tag{11}$$

$$\frac{U^2}{u_{\text{rms}}^2} = 12.55\left(\frac{X}{M} - 3.7\right), \text{ for the two-phase flow, } M = 10 \text{ mm}, \tag{12}$$

where $u_{\text{rms}} = \langle u'^2 \rangle^{1/2}$ is the fluctuating velocity of the gas flow. According to these formulae, in the two-phase flow the particles tend to damp the turbulent fluctuations.

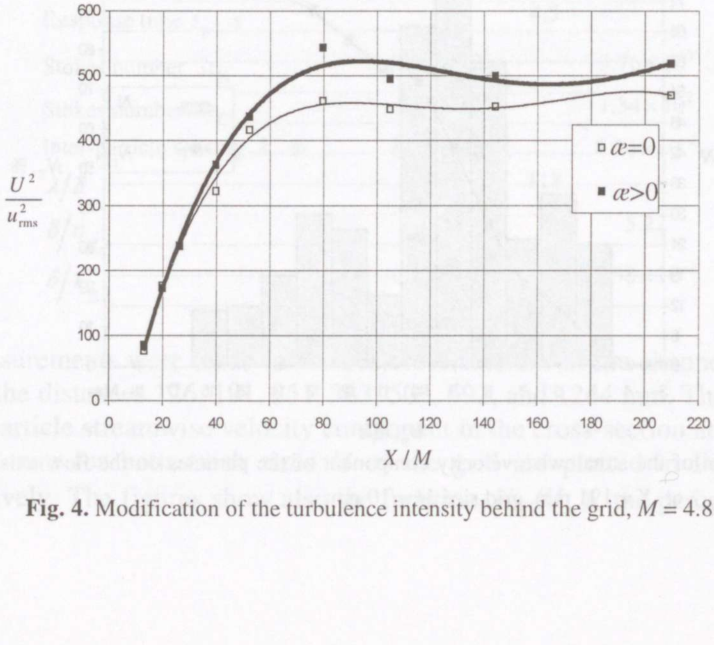

Fig. 4. Modification of the turbulence intensity behind the grid, $M = 4.8$ mm.

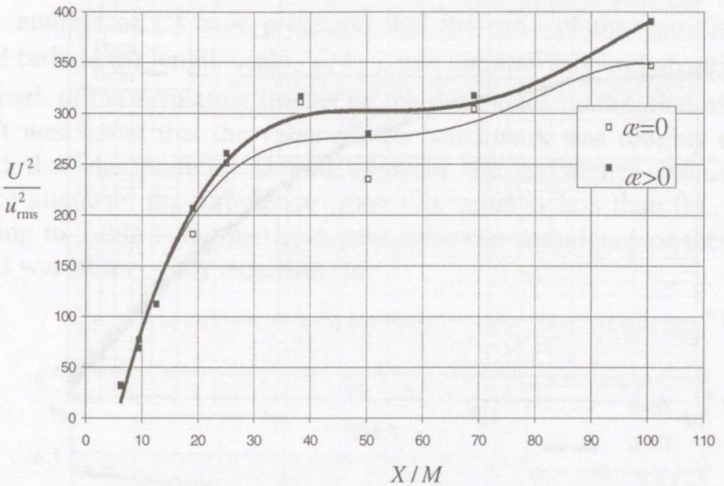

Fig. 5. Modification of the turbulence intensity behind the grid, $M = 10$ mm.

The experimental investigations show that the turbulence intensity (reciprocal to the decay) behind the grid decreases until a certain cross-section at $X/M \cong 90$ for $M = 4.8$ mm (Fig. 4) and until the cross-section $X/M \cong 40$ for $M = 10$ mm (Fig. 5), and then remains almost constant. This corresponds roughly to the turbulence in a channel without the turbulence-generating grid and it is conditioned by the initial turbulence. The decreasing of the turbulence intensity in cross-sections behind $X/M \cong 70$ (Fig. 5) is caused by the influence of the channel flow dominating there. From Figs. 4 and 5 one can also conclude that the particles with mass loading of 0.05 (kg dust)/(kg air) brought about a decrease of the turbulence intensity. The effect of attenuation of the turbulence intensity by rough particles is more pronounced for smaller grid size.

The energy spectra for the streamwise velocity fluctuations of the gas were calculated for laden and unladen flows at the distances 126 and 383 mm from the grid. The initial energy spectra of the velocity fluctuations were smoothed with the help of the averaging procedure over a number of the neighbouring values [7,8]. The results are shown in Figs. 6–9. One can see that for $M = 4.8$ mm the turbulence energy decreases at higher frequencies. For the larger size of the grid ($M = 10$ mm), one can hardly notice any difference in the energy spectra for single-phase and two-phase flows. This is mainly caused by low mass loading of the flow inasmuch as we deal with dilute gas–particle two-phase flows.

To evaluate the range and nature of the particle influence on the turbulence structure of the considered grid-generated two-phase flow, we calculate the key parameters. They are the Stokes numbers, St_{K} and St_{E}, by which we can estimate the particle response to the small and large turbulent eddies, the inter-particle spacing λ by which we can assess the particles contribution to the attenuation/augmentation of the turbulence intensity, and the correlation of the particle size with different turbulence lengths (the Kolmogorov and Euler scales).

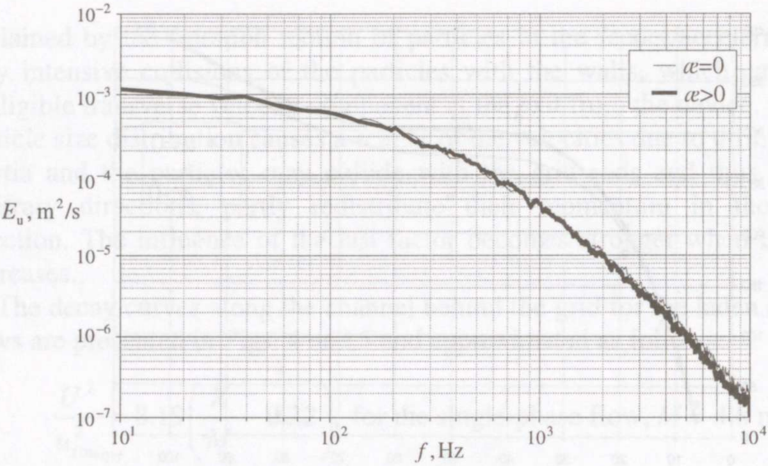

Fig. 6. The energy spectra for single and two-phase flows at $X = 126$ mm, $M = 4.8$ mm.

Fig. 7. The energy spectra for single and two-phase flows at $X = 126$ mm, $M = 10$ mm.

For both time scales we have $St_K >> 1$ and $St_E >> 1$ (Table 1) and thus, according to [10], our glass particles can be considered to be large particles. Moreover, the particle size exceeds the size of the smallest turbulent eddies $\delta/\eta_K = 6.31$ for the smaller grid and 5.22 for the larger one and therefore we can expect the turbulence production by wakes induced by rough particles. On the other hand, for the considered dilute two-phase flow with $æ << 1$ and $\beta << 1$, the motion of the particles should not produce a significant effect on the flow.

The authors of [1] have predicted that the ratio of the particle size to the integral turbulence length scale, δ/L_{E}, can qualitatively and quantitatively be a benchmark of the admixture impact on the turbulence modulation of the primary fluid. It was found that the value of this benchmark was roughly equal to 0.1. Beyond that the particles should augment the turbulence intensity and the particles attenuate the turbulence when this value is less than 0.1. In our case, according to Table 1, the particles must attenuate turbulence of the carrier flow and that was observed by experiments.

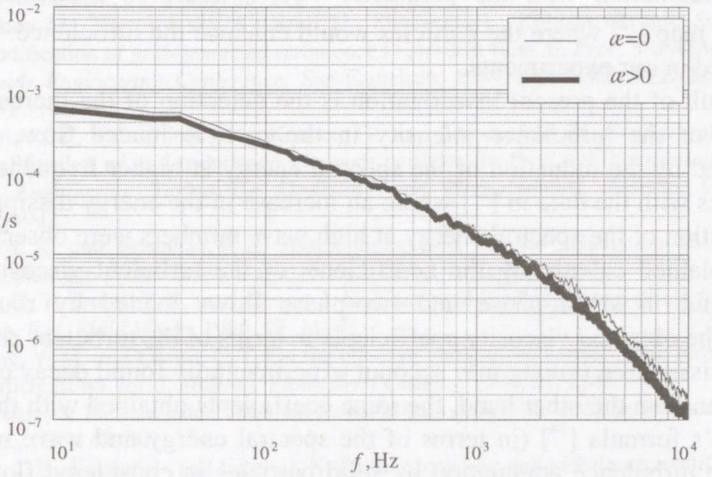

Fig. 8. The energy spectra for single and two-phase flows at $X = 383$ mm, $M = 4.8$ mm.

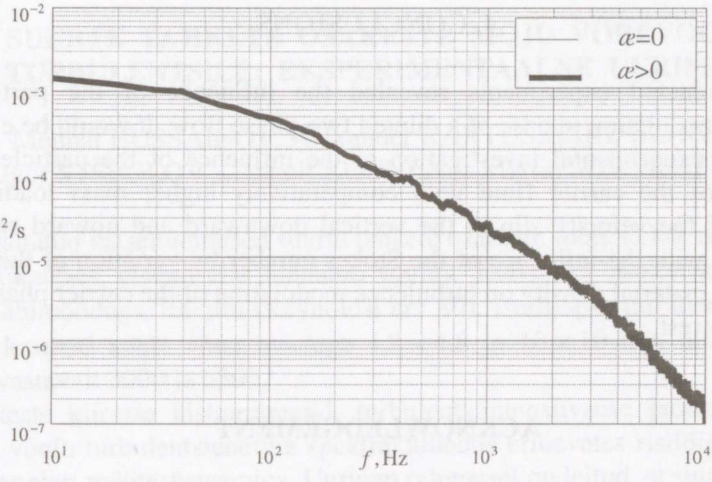

Fig. 9. The energy spectra for single and two-phase flows at $X = 383$ mm, $M = 10$ mm.

While studying the turbulence modulation by particles, the authors of [11] have emphasized the significance of the ratio of the inter-particle spacing to the particle size, λ/δ, by evaluating the two-way coupling effect. In the Elghobashi map [12] the inter-particle spacing, normalized to the particle diameter, is one of the key parameters which determines the influence of the particles on the turbulence modulation. In our case $\lambda/\delta = 118$ which is close to the limit value by which the two-way coupling regime is of considerable importance. Hence, we are in a transition region where one can expect only small influence of the particles on the turbulence modulation. On the basis of the calculated values of St_{K} and St_{E} in combination with the parameter λ/δ we are in a domain of the Elghobashi map [12] where the particles would enhance the turbulence. That was not observed in our experiments.

One result of the present investigation is the detection of the increase of the decay rate of the turbulence intensity in the particle loaded flow, which is accompanied by the reduction of the spectral energy at higher frequencies. This result agrees with the data in [13] where an increase in the energy dissipation rate and a reduction of the spectral energy at high wave numbers were observed. That can be explained calculating the coefficients of the turbulent viscosity of the primary fluid in single-phase and two-phase flows loaded by rough solid particles. The obtained viscosity coefficients in terms of the turbulent energy and rate of its dissipation (taking into account experimentally found decay curves for the flows) and, on the other hand, the same coefficients obtained with the help of Heisenberg's formula [14] (in terms of the spectral energy and wave numbers), indicate the turbulence attenuation by solid particles in considered flows. Such tendency was predicted in [7,8].

4. CONCLUSIONS

The conducted experiments revealed the influence of the particles on turbulence modulation in case of a diluted two-phase flow. It would be expedient to continue experimental investigation of the influence of the particles on the turbulence of the carrier fluid with comparatively higher mass loading. The influence of the velocity slip in the vertical downward and upward two-phase flows along with the influence of the Stokes number by variation of the particle size and the material density on turbulence modulation of the carrier phase is also of major interest.

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SUURTE TAHKETE OSAKESTE MÕJU VÕREVOOLU TURBULENTSILE: EKSPERIMENTAALNE UURIMINE

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On esitatud katsetulemused suurte tahkete osakeste mõju kohta võreturbulentsile vertikaalses, ülevalt alla suunatud voolus. Tahketeks osakesteks olid klaaskuulid läbimõõduga 700 μm (Reynoldsi arv 80). Isotroopse turbulentsivälja saamiseks kasutati kahte võret avadega 4,8 × 4,8 ja 10 × 10 mm ning Reynoldsi arvuga vastavalt 3000 ja 6300.

Osakeste kiiruste histogrammid, turbulentsiintensiivsuse jaotus piki voolu telge ja voolu turbulentsienergia spektraaltihedus erinevates ristlõigetes määrati laser-Doppleri mõõtesüsteemiga. Uuringu tulemusel on leitud, et suured osakesed põhjustavad voolu turbulentsiintensiivsuse sumbumist ja energiaspektri tiheduse vähenemist kõrgete sageduste piirkonnas.