Final report on the project 'Investigation of the influence of microparticles on turbulent mixing'

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1 Introduction

One of the most important problems in two-phase flows is turbulence modification by the particles. In some cases, the turbulent kinetic energy decreases by 80% compared to the single-phase flow [6]. Such important changes must have an effect on mass and heat transfer. But, there are configurations in which no remarkable turbulence modification occurs and other ones in which an enhancement of the turbulence by the particles is observed. Up to now, the physical mechanisms behind that are so poorly understood that it cannot be safely predicted how turbulence will be modified under given conditions.

For a better analysis of the different scales time dependent fluctuations of the process variables are often transferred to the frequency space using Fast Fourier Transforms (FFT). In such a spectrum the ranges of macroscopic changes caused by the main flow and of microscale processes caused by molecular transport can be separated from the turbulent fluctuations by their corresponding range of wave numbers [4]. The main region of the spectra of concentration and temperature can be analysed in a similar manner considering the values of the transport coefficients while the relation between the kinetic energy spectrum and the other two is more complicated.

Up to now, the influence of solid particles on turbulent flow structures has been studied mainly for the velocity field. A good survey on that is given by Pan et al. [3] who also present own numerical results using Direct Numerical Simulations. A numerical analysis of the temperature spectrum has been performed by Lisin and Hetsroni [2] for solid particles in a gas. They assumed a two-phase system, in which the turbulence is homogeneous and isotropic, the particles are small and the fluctuating component of the fluid temperature is small compared to the mean temperature. The volume fraction of the particles V_{pc} is small and its fluctuations are ignored. They found that the presence of particles (10 μm and 100 μm) with low particle Reynolds numbers can modify the structure of the temperature spectrum of the fluid, damping the intensity of fluctuations in the high frequency range. Interphase heat transfer causes smoothing and it is intensified when radiation is present. As a consequence, the particles reduce the amplitude of the temperature spectrum. Lisin and Hetroni performed a theoretical analysis of temperature fluctuations only. The velocity field was not analysed in their work and, therefore, the influence of particles on the heat transfer via changes in velocity fluctuations is not considered.

The goal of our investigations is the development of a measurement technique for the temperature spectra at certain locations of the turbulent flow in a stirred tank and the study of the influence of microparticles on this spectrum. Non-invasive optical measurements require a transparent medium, which cannot be gained for fine-disperse systems. Therefore, a probe was used in a way that there was only a minimal disturbance of the flow.

2 Experimental set-up and measurement technique

The experiments were performed in a stirred tank of diameter D = 400 mm, filled with water to a height equal to the tank diameter, H = D (see Fig. 1). A four-blade PBT impeller of diameter d = 133 mm was used. The continuous phase was water, dispersed phase were glass particles with a diameter of 100 μm and a density of 2430 kg/m^3. Volume fractions of solid particles were varied from 1% to 5%. The initial temperature in the stirred vessel was 20°C. Three impeller speeds were realised: n = 300 rpm, 400 rpm and 500 rpm, corresponding to Reynolds numbers beyond 90 000. For 400 rpm and 500 rpm the particles were suspended completely to the top of the liquid hight. For 300 rpm and a volume fraction of 5% the suspension height was only 80%. Consequently, at the upper measurement position the volume fraction was significantly lower and at the lower position it was slightly higher than the average value.

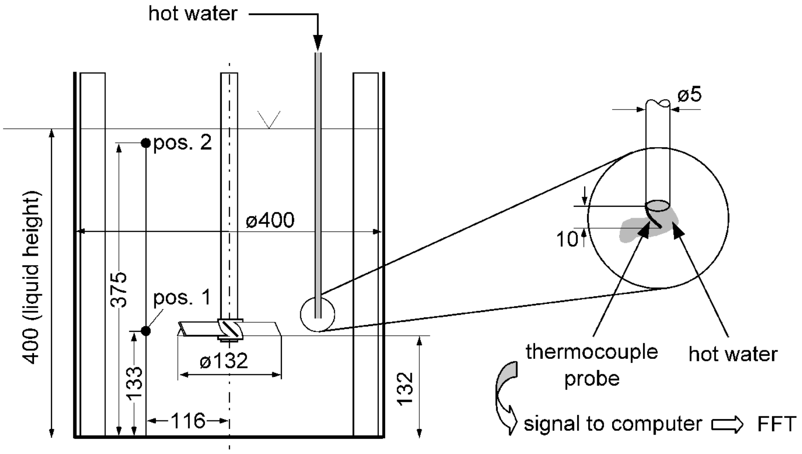

Figure 1: Experimental set-up

As optical techniques cannot be used due to the turbidity of the two-phase suspension an invasive measurement technique – thermoanemometry – was applied. Criteria for the applicability of this technique are: minimal disturbance of the flow, high sensitivity to temperature fluctuations and high sampling rate. Based on this a system was developed which consists of a small tube for hot water injection (temperature of 60°C and volume flow of 4.68 l/h) as shown in Fig. 1. Below the hot water inlet the thermocouple type T with a time constant of 10 ms and a diameter of 250 μm was located. Experiments were carried out for two different positions h. Measurements were carried out at h1 = 133 mm from the bottom of the tank and at h2 = 375 mm, in both cases 116 mm away from the tank axis.

The signal measured in time domain has to be converted to the frequency domain by Fast Fourier Transform in order to obtain the required spectrum.

In order to achieve reliable results different problems had to be solved: water has to be added with a constant temperature, strong density differences between the water in the tank and the added water have to be avoided, a sufficient measurement frequency to satisfy the Nyquist criterion has to be chosen and the signal has to be transferred from the thermocouple to the computer without electronic falsification or damping. The last point is still in progress and restricts present descriptions to the low frequency range.

Another factor that affects the quality of results is the sampling rate. The sensitivity of a thermocouple is given by Elsner and Drobniak [1]:

$$f_w = \frac{1}{2\pi\tau_w} \tag{1}$$

where τ_w is the time constant of the thermocouple probe. For the thermocouple used in these experiments the time constant is 10 ms yielding $f_w = 15.9$ Hz. It means that data collected at higher frequencies have no physical meaning. On the other hand the Nyquist criterion must be satisfied [5]:

$$f_c = \frac{1}{2dt} \tag{2}$$

where dt is the time between two samples in seconds and is a critical frequency. For the given frequency of about 16 Hz the Nyquist criterion is satisfied for a time step of 30 ms.
It has to be stressed that the spectra obtained are not averaged. But, for a clear interpretation of the results the fluctuations found are too strong. Therefore, a damping procedure is required. The best solution would be to carry out a large number of measurements and average their spectra for each frequency. This procedure was followed with six measurements per configuration but the remaining noise was still too large. Due to time constraints it was not possible to perform a sufficient number of experiments to get smoother temperature spectra. Instead, for each data point ten preceding and ten successive points of the spectrum are used to get an averaged value at that point. The spectra before and after smoothing are presented in Fig. 2.

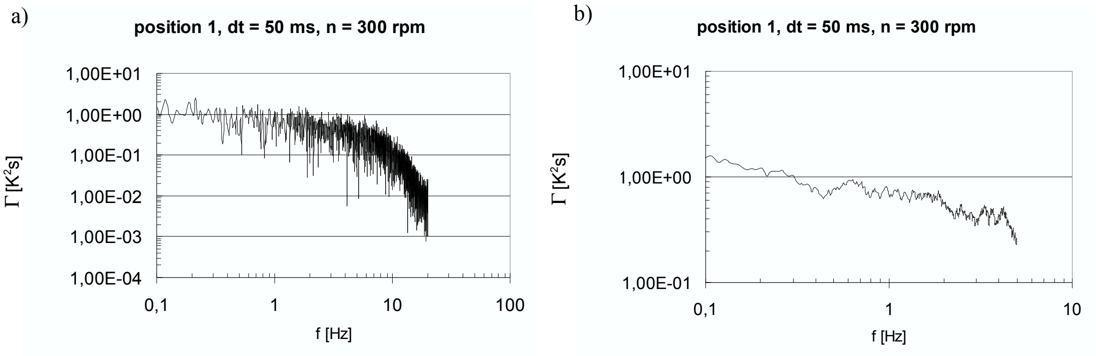

Figure 2: Temperature spectra. a) before smoothing b) after smoothing

Due to the applied amplifier frequencies higher than 4 Hz are damped by the filter and can therefore not be interpreted. Therefore, all spectra discussed in the next section had to be reduced to frequencies below 4 Hz. An improved data handling to avoid this problem is being developed.

3 Results

3.1 Influence of the particle concentration on the temperature spectra

The influence of particles on the temperature spectrum is presented in Fig. 3. For two different stirrer speeds the single-phase flow is compared to two-phase systems with 1% and 5% volume fraction of particles. For a stirrer speed of n = 300 rpm noticeable differences between the three cases can be observed in the frequency range considered. The temperature spectrum of the single-phase flow shows higher amplitudes than the spectra of the two-phase systems. This effect is obvious for a volume fraction of 1% and even more pronounced for a volume fraction of 5%. A similar trend occurs at a stirrer speed n = 500 rpm.

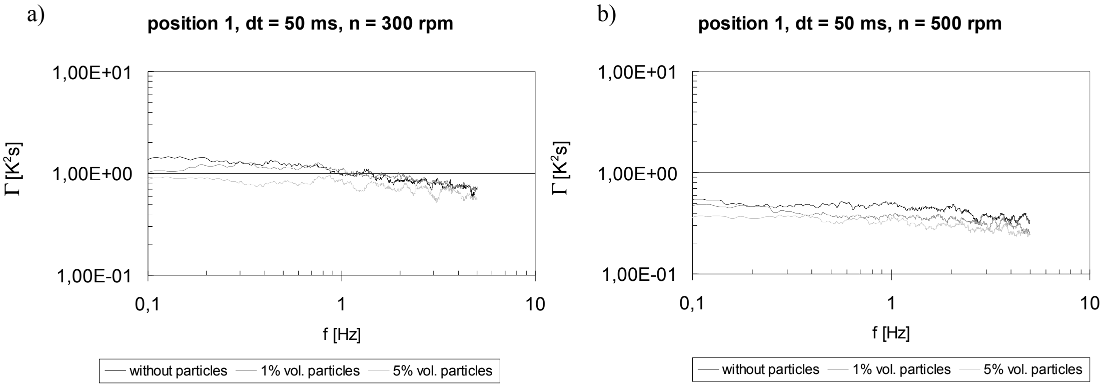

Figure 3: Temperature spectra for flow with and without particles. a) n = 300 rpm, b) n = 500 rpm

The quantity Γ characterizes fluctuations in temperature in relation to the frequency. The spectrum of temperature fluctuations for the single-phase system with a stirrer speed of n = 300 rpm is on the level of 1 K^2s, while for a two-phase system with 5% particles under the same conditions these fluctuations are around 0,8 K^2s. An increase of the stirrer speed to n = 500 rpm causes a noticeable decrease of the level of fluctuations for both single- and two-phase systems.

3.2 Influence of the measurement position on the temperature spectra

A change of the measurement position of the probe allows one to study the different structure of the spectra at the different locations in the stirred vessel. The temperature spectra for different stirrer speeds obtained for different positions are presented in Fig. 4.

Fig. 4a shows results for the position 1 where the probe was located at the level of the stirrer and Fig. 4b shows the corresponding spectra for position 2 which was 25 mm below the water surface. In both cases the volume fraction was 5%. For the measurement position h2 and stirrer speed n = 300 rpm the results are not representative for a two-phase system because the suspension height is too low and therefore not considered here.

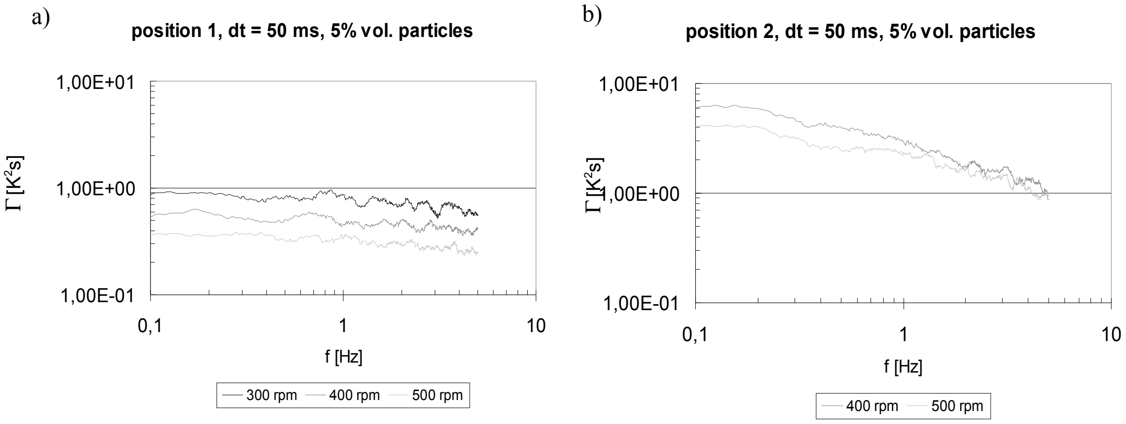

Figure 4: Influence of measurement position (s. Fig. 1) a) position 1: h1 = 133 mm, b) position 2: h2 = 375 mm from bottom

It can clearly be seen in Fig. 4a that both parameters varied affect the results of the measurements: proximity of the stirrer and intensity of mixing. As mentioned before, intensive mixing damps temperature fluctuations – the highest values of Γ are obtained for the smallest stirrer speed. The flow structure in the proximity of the stirrer depends strongly on the power input which is obvious from Fig. 4a, where the mean amplitude changes from 0,8 K^2s for n = 300 rpm to 0,3 K^2s for n = 500 rpm. At location 2, T is in the order of one magnitude larger than at 1 because the turbulence intensity is much smaller at this position.

Further activities require primarily the improvement of the measurement technique in a way that frequencies up to values of 500 Hz to 1000 Hz can be reliably detected. Later on, turbulence models considering the phase interaction shall be developed based on the measurements.

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