Available online at www.sciencedirect.com
SCIENCE DIRECT®
PERGAMON
International Journal of Multiphase Flow 29 (2003) 701–718
International Journal of Multiphase Flow
www.elsevier.com/locate/ijmulflow

Analysis of collision effects for turbulent gas-particle flow in a horizontal channel. Part II. Integral properties and validation

M. Sommerfeld *, J. Kussin

Institut für Verfahrenstechnik, Fachbereich Ingenieurwissenschaften, Martin-Luther-Universität Halle-Wittenberg, D-06099 Halle (Saale), Germany

Received 21 August 2002; received in revised form 29 January 2003

Abstract

The phenomena of particle–wall collisions including wall roughness and inter-particle collisions in a horizontal channel flow are analysed in detail by numerical calculations on the basis of the Lagrangian approach. In order to assess the effects of particle–wall collisions and inter-particle collisions independent on other phenomena, two-way coupling is neglected in this study. Integral values of the particle phase properties, such as mean velocities and fluctuating components averaged over the channel height are used to demonstrate the consequences of both transport effects. The ratios of the fluctuating components are determined in order to assess the unisotropy of the particles fluctuating behaviour. Additionally, a channel with a larger height is considered in order to provide information on the scale-up of the effects observed in a narrow channel. For validating the Lagrangian models describing particle–wall and inter-particle collisions, numerical calculations for different particle size and mass loading are compared with measurements by phase-Doppler anemometry in the developed region of a channel with 35 mm height and 6 m length. The good agreement between measurements and calculations allow to conclude that the transport phenomena wall collisions and inter-particle collisions are modelled appropriately.

Keywords: Gas-particle flow; Horizontal channel; Lagrangian particle tracking; Wall collisions; Wall roughness; Inter-particle collisions; Angular velocity; Validation

* Corresponding author. Tel.: +49-3461-46-2879/2876; fax: +49-3461-46-2878.
E-mail address: martin.sommerfield@iw.uni-halle.de (M. Sommerfeld).

0301-9322/03/$ - see front matter © 2003 Published by Elsevier Science Ltd.
doi:10.1016/S0301-9322(03)00033-8

1. Introduction

Pneumatic conveying of solid particles in channel or pipe flows is of great technical importance and is characterised by particle phase segregation due to gravity and particle inertia. Similar two-phase flow systems are found in cyclone separators and classifiers. Due to the presence of the confinement in these systems, the collisions of the solid particles with the walls play an essential role in the particle transport process. The wall collision frequency is directly responsible for the additional pressure drop due to the solids as a result of the momentum and energy loss involved in the deformation process (Adam, 1960). Additionally, wall roughness considerably affects the wall collision process (Tsuji et al., 1987; Sommerfeld and Huber, 1999) and causes an enhancement of the wall collision frequency in pipes or channels for larger particles. On the other hand, the wall collision frequency is reduce for smaller particles ($\tau_P < 50$ ms) as a consequence of wall roughness (Sommerfeld, 2003).

The particle inertia and the effect of gravity will cause a separation of the mixture, whereby rather dense ropes of solids may be formed (Yilmaz and Levy, 2001). The increasing local solids concentration supports the occurrence of inter-particle collisions. This results in a dispersion of the particles out of a dense rope due the transfer of momentum from the main stream direction to the transverse component. Hence, collisions between particles may cause a destruction of dense ropes and therefore also will have a drastic effect of the particle transport in such two-phase systems. In a previous study by Sommerfeld (2003) both phenomena have been analysed based on numerical calculations by the Lagrangian approach for a narrow horizontal channel flow.

The present paper is an extension of this work and introduces results for integral properties of the particle phase (i.e. averaged across the channel height) in order to easily assess the effect of wall collisions including different degrees of roughness and inter-particle collisions. For providing information on the scale-up behaviour of the two phenomena also a higher channel is considered. Eventually, the numerical calculations are compared with detailed experiments by phase-Doppler anemometry (PDA) in order to validate both models.

2. Integral properties and angular velocity

In the following section integral effects of wall collisions, wall roughness and inter-particle collisions on the behaviour of spherical particles with different size and a density of $\rho_P = 2.5$ g/cm^3 in a horizontal channel of 35 mm height and a length of 6 m are introduced. The gas-flow field (i.e. mean velocity and turbulence) was prescribed for a fully developed channel flow with an average velocity of 18 m/s and two-way coupling was neglected. This implies that constant profiles of the mean velocities and mean fluctuating components for the gas-phase are given along the channel. For the streamwise gas-velocity profile a potential law with an exponent of 1/7 was used. The rms-values of the fluid velocity fluctuations in the streamwise and lateral directions were taken from the measurements of Laufer (1950) by accounting for the considered average gas velocity. The integral time and length scales were determined as described by Sommerfeld (2003). The gas density was given a value of 1.18 kg/m^3 and the dynamic viscosity was selected to be 18.8×10^{-6} N s/m^2. The particle phase was simulated by the Lagrangian approach using all the relevant forces and the models for particle–wall and inter-particle collisions described previously (Sommerfeld, 2003). Calculations were performed for a smooth wall and with high (HR) and low roughness (LR) as defined by (Sommerfeld, 2003). In the calculations mono-sized particles in the size range between 30 and 700 μm are considered. The averaged particle response times and estimates of the particle Stokes numbers calculated with the integral time scale of turbulence on the centre-line are provided in Table 1 for a channel height of 35 and 70 mm. In order to get statistical reliable data typically about 20,000 parcels are tracked sequentially through the flow field.

A summary of integral results for cases with and without wall roughness is shown in Fig. 1 using the mass loading as a parameter. For the determination of these data, the particle velocity was averaged across the channel height after a conveying distance of 6 m and normalised by the average air velocity. It should be noted, that the numerical calculations with $\eta = 0$ are without inter-particle collisions, whereas all other results account for collisions. It is clear that both, the increase of particle response time (i.e. particle size) and wall roughness causes a decrease in the horizontal component of the averaged particle velocity which is the combined action of momentum loss due to wall collisions and the particle inertia to follow the flow. With increasing loading for a given situation, only a slight decrease of the mean velocity is observed. Additionally, the result with a low roughness (Sommerfeld, 2003) shows, as expected, that the average particle velocity is between the other two cases.

The local average of the particle fluctuating energy may be simply calculated from the following equation by accounting for the two main velocity components in a two-dimensional situation:

$$E_{\mathrm{P}} = \frac{\overline{u_{\mathrm{P}}'^2} + \overline{v_{\mathrm{P}}'^2}}{U_{\mathrm{av}}^2}$$

By averaging these local values across the channel in the developed flow one obtains $E_{\mathrm{P\,av}}$. For different mass loading and the cases with and without wall roughness, the results are summarised in Fig. 1(b). First of all it is obvious, that the fluctuating energy of the particles is much lower in

Table 1
Characterisation of particles used for the numerical calculations

Particle diameter [μm]	Channel 35 mm		Channel 70 mm	
	Averaged particle response time [ms]	Stokes number [–]	Averaged particle response time [ms]	Stokes number [–]
30	5.4	1.4	5.4	0.71
60	17.6	4.6	18.8	2.5
110	42.6	11.2	47.4	6.2
195	93.0	24.3	104.5	13.8
300	158.0	41.4	182.7	24.0
500	288.6	75.5	334.7	44.0
700	417.2	109.2	488.7	64.3

The particle response time is an average of all particles tracked through the channel and accounts for non-linear drag ($U_{\mathrm{av}} = 18$ m/s, $\eta = 1.0$, with wall roughness and inter-particle collisions); the Stokes number is defined as $St = \tau_{\mathrm{P}}/T_{\mathrm{L}}$, where the integral time scale on the centre-line of the channel is used; channel 35 mm: $T_{\mathrm{L}} = 3.8$ ms; channel 70 mm: $T_{\mathrm{L}} = 7.6$ ms.

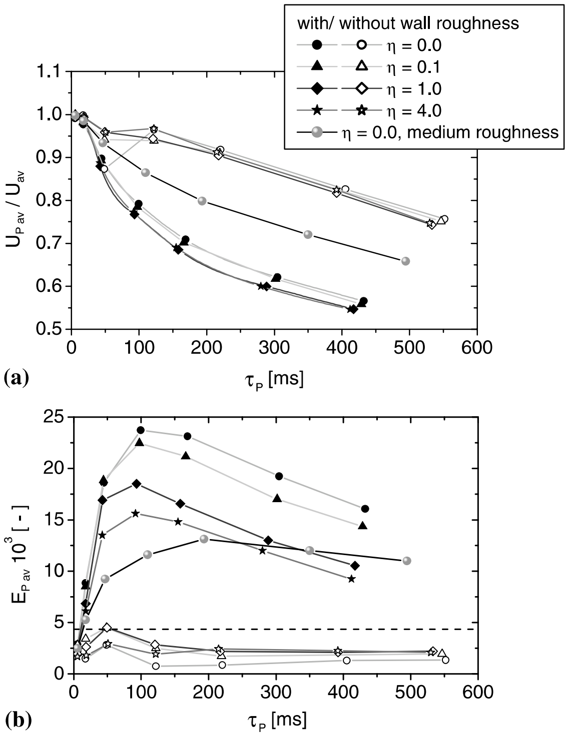

Fig. 1. Calculated average horizontal component of particle mean velocity (a) and associated averaged fluctuating energy (b) as a function of particle response time, illustrating the effect of wall roughness, HR and LR ($\eta = 0.0$ indicates the result without inter-particle collisions, dashed line: fluctuating energy of the gas-phase, channel height $H = 35$ mm, average gas velocity $U_{av} = 18$ m/s).

the case without wall roughness than with wall roughness and mostly below the fluctuating energy of the gas-phase. Moreover, only a slight increase is observed with increasing mass loading. Some stronger variations are found in the region of the minimum of the wall collision mean free path where the particle transport changes from saltating motion to a wall to wall bouncing behaviour (Sommerfeld, 2003).

With wall roughness, a rapid increase of the fluctuating energy with particle response time is observed up to a value of about 50 ms in this case. Then a maximum is reached and beyond about 100 ms the energy of fluctuation decreases again with response time. This behaviour may be related to wall collisions and particle inertia. Initially, small particles are strongly dispersed by wall roughness and one finds very large values of the wall collision mean free path. For larger response times, the wall collision mean free path remains almost constant and is considerably smaller than without roughness. Hence, the decrease of fluctuating energy (i.e. beyond $\tau_P \sim 100$ ms) is caused by particle inertia. The effect of inter-particle collisions is very clear for the larger roughness. Increasing mass loading and hence inter-particle collision frequency, results in a damping of fluctuation energy due to the dissipation of energy by collisions between particles which are in the present case of course inelastic. Therefore, also the material of the particles and the collision properties are of importance. In the present calculations a restitution ratio of 0.9 and a friction coefficient of 0.4 was applied. The case with smaller roughness and without inter-particle collisions lies again between the no-roughness and high-roughness case.

As already noted previously by several authors (see Tanaka and Tsuji, 1991; Sommerfeld, 1995), inter-particle collisions will cause the fluctuating velocity of the particle phase to become more isotropic. In order to demonstrate this effect and to reveal the influence of wall roughness, the ratio of the fluctuation components for the particles averaged across the channel height is plotted in dependence of particle response time (Fig. 2). As a parameter, the particle mass loading is used, which has a direct correlation with the inter-particle collision frequency. Again the result is considerably different for the case with and without wall roughness.

For a smooth wall, an increase in particle response time is associated first with an increase of the fluctuation ratio to a maximum value and then followed by a decrease. The maximum is found in the region where the particles mainly bounce along the lower wall, i.e. one has a strong saltating motion. Hence, in this regime the particle fluctuation is strongly non-isotropic and the streamwise component is dominating. With increasing particle response time the ratio decreases again and approaches an almost constant value for large particles. A distinct decrease is observed with increasing mass loading and hence increasing collision frequency over the entire size range considered. With inter-particle collisions and at higher mass loading the ratio of the particle fluctuation velocity reaches some kind of equilibrium value around 1.5.

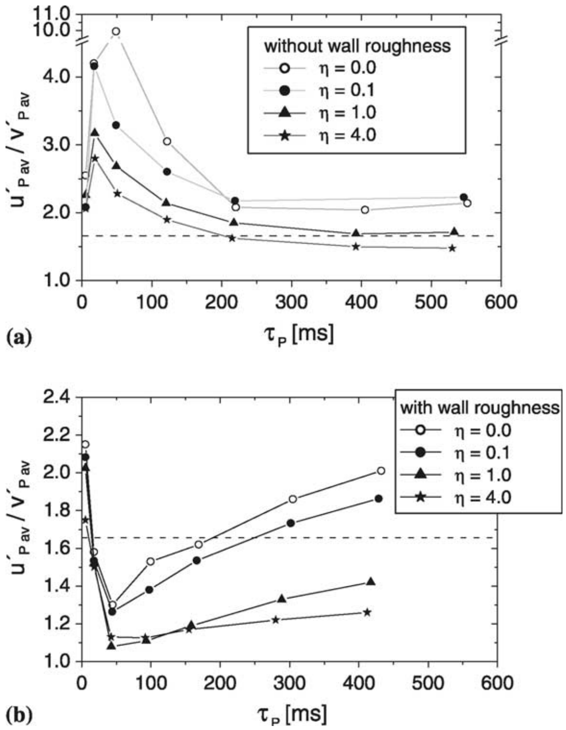

Fig. 2. Calculated ratio of particle fluctuating velocity averaged across the channel: (a) smooth channel, (b) channel with wall roughness, HR ($\eta = 0.0$ indicates the result without inter-particle collisions, dashed line: ratio of the gas-phase fluctuating velocities, $H = 35$ mm, $U_{av} = 18$ m/s).

With wall roughness, the fluctuating behaviour of the particles is completely different. In the range of small particles, one finds with increasing response time a drastic drop of the fluctuation ratio to a minimum value which is with inter-particle collisions and higher loading around a value of 1.1. Then the ratio increases continuously with particle response time as a result of the irregular wall bouncing. For a wide range of the considered particle response times, the fluctuating motion of the particles become more isotropic with increasing mass loading, caused by inter-particle collisions. However a saturation is reached beyond a mass loading of 1.0.

Eventually, it will be also demonstrated, that the angular velocity of the particles is strongly affected by wall roughness and inter-particle collisions. For this purpose Fig. 3 shows the angular velocity averaged across the channel in the region of developed flow. First of all it is obvious, that the average values are only negative. Per definition the angular velocity becomes positive for a collision with the upper and negative for a collision with the lower wall. Hence, the negative angular velocity (i.e. clockwise rotation) implies that the particles will mainly collide with the lower wall of the channel. Naturally, the near-wall values will be considerably higher for smaller particles, since the angular velocity induced by a wall collision is proportional to the reciprocal value of particle size. There exists of course a strong correlation between angular velocity and particle response time due to the viscous interaction with the fluid. For both cases, i.e. with and without wall roughness, the modulus of the angular velocity rapidly increases with the response time. The average angular velocity is higher for the larger particles due to inertial effects, but also partly resulting from the higher wall collision frequencies (i.e. depending on the case considered). Additionally, the time scale for the damping of the particle rotation due to the viscous interaction with the gas increases with particle size. This effect is illustrated in Fig. 4(a) for 30 μm particles and a rough wall. In the vicinity of the walls these small particles reach very high average angular velocities. Since the particles interact reasonably well with the air flow, the areas of high angular velocity are restricted to the near-wall regions. The slightly higher collision rate with the bottom wall is reflected also in higher negative angular velocities. In the core region the average angular velocity is almost zero. Even in the case of wall roughness the particle bouncing frequency with the lower wall is higher and the angular velocity is negative over the entire channel for low mass loading. The effect of saltating motion is of course stronger without roughness, so that for larger

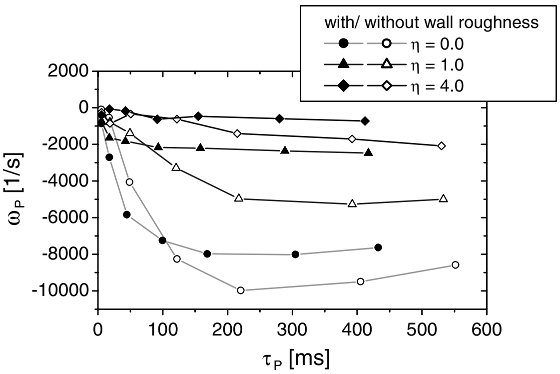

Fig. 3. Calculated angular velocity of the particles averaged across the channel for different mass loading and with (HR) and without wall roughness ($H = 35$ mm, $U_{av} = 18$ m/s).

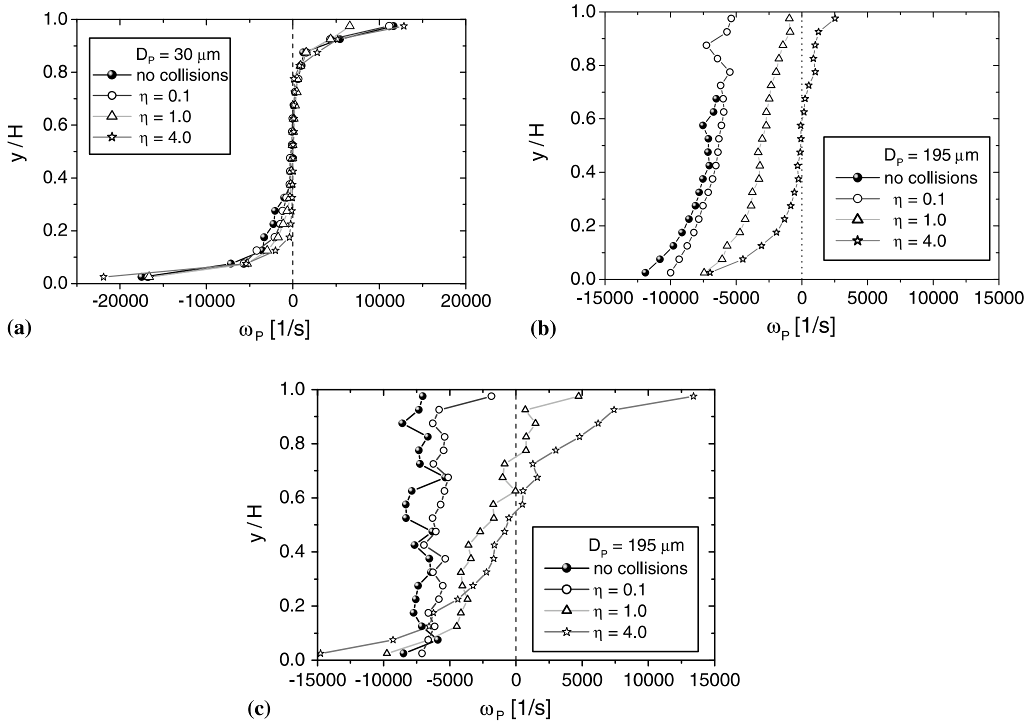

Fig. 4. Calculated profiles of angular velocity for different cases at increasing mass loading in the developed region of the channel ($H = 0.35$, $U_{av} = 18$ m/s): (a) rough wall (HR), 30 µm particles; (b) smooth wall, 195 µm particles; (c) rough wall (HR), 195 µm particles.

particles (i.e. $\tau_P > 100$ ms) the modulus of the angular velocity is higher without roughness (Fig. 3). The increase of mass loading and hence the increase of the inter-particle collision frequency causes a considerable reduction in the modulus of the angular velocity especially in case of larger particles, for both conditions, i.e. with and without wall roughness. This originates from an increase of lateral dispersion due to inter-particle collisions (Sommerfeld, 2003). Hence, the collision probability with the upper wall increases with mass loading resulting in an increase of particles with positive angular velocity in the region close to the upper wall as illustrated by Fig. 4(b) and (c) without and with roughness, respectively. For the highest mass loading considered, almost symmetric profiles of the angular velocity with respect to the centre line are established, resulting in low averaged values of the angular velocity given in Fig. 3.

3. Effect of channel height

Additionally, a number of calculations were performed for a larger channel height, namely $H = 70$ mm in order to assess the scale-up behaviour of the findings described above. For allowing also developed flow conditions for this case the channel had a length of 12 m. The profiles of the mean velocity and mean fluctuating velocities are specified in the same way as described above. Compared to a narrow channel two main effects are observed:

- The integral time scale of turbulence is increased and hence the smaller particles should be better dispersed by turbulence (Table 1).
- The wall collision frequency for inertial particles is reduced since the distance between the walls increases and hence the particles have more time to respond to the flow.

These effects are illustrated in Fig. 5 where the trajectories of 60 μm particles in the case of wall roughness without inter-particle collisions are shown for both channel heights. It should be noted, that both graphs are not in scale. For the considered condition the wall collision frequency is considerably higher for the narrow channel (i.e. $H = 35$ mm) and in the wider channel the saltating motion of the particles is more pronounced. This of course has a dramatic effect on the averaged profiles of the particle phase properties as shown in Fig. 6 for smaller (60 μm) and larger (195 μm) particles. The reduction of wall collision frequency for the larger channel of course results in a decrease of the particle velocity fluctuations (Fig. 6(c) and (d)) and therefore the particle vertical dispersion is also reduced (Fig. 6(a)). These effects are more pronounced for the smaller particles. Moreover, the particle mean velocity is higher for the larger channel, since the reduced wall collision frequency also is coupled with a reduced momentum loss due to wall collisions (Fig. 6(b)). Additionally, as a result of the reduced transverse dispersion, especially for the 60 μm particles, the horizontal mean velocity component is closer to that of the gas-phase. Similarly, the velocity fluctuations for the 60 μm particles become lower than those of the gas-phase for higher channels. For the large particles, the velocity fluctuations are only slightly lower in the case of the higher channel, which also results in only small modifications of the profiles of particle mass flux (Fig. 6(a)).

The integral properties (i.e. averaged across the channel height) for the particle phase fluctuating behaviour are summarised in Fig. 7 for both channel heights, demonstrating again the reduced fluctuation energy of the particles in case of larger channels up to a particle response time of about 300 ms. For larger particles the fluctuating energy becomes about the same, since such inertial particles bounce from wall to wall in both types of channels. When introducing inter-particle collisions and increasing mass loading again the fluctuating energy of the particles is reduced, due to the dissipative nature of particle collisions. Additionally, the fluctuating behaviour of particles in the wider channel is more isotropic for response times larger than about 50 ms. When loading and the importance of inter-particle collisions increase, a further isotropisation of

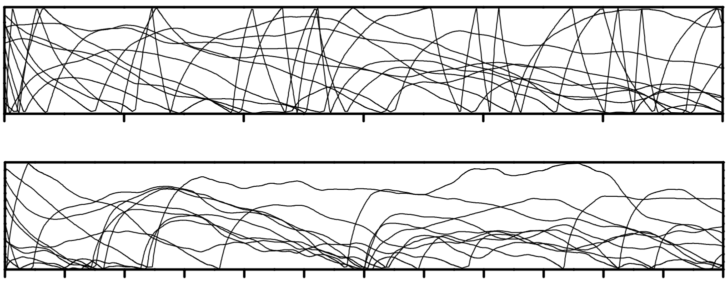

Fig. 5. Calculated particle trajectories in horizontal channels with different height, with wall roughness (HR): (a) channel height 35 mm, length 6 m; (b) channel height 70 mm, length 12 m (length and height of the graphs correspond to these dimensions, particle diameter 60 μm, $U_{av} = 18$ m/s, $\eta = 0.1$).

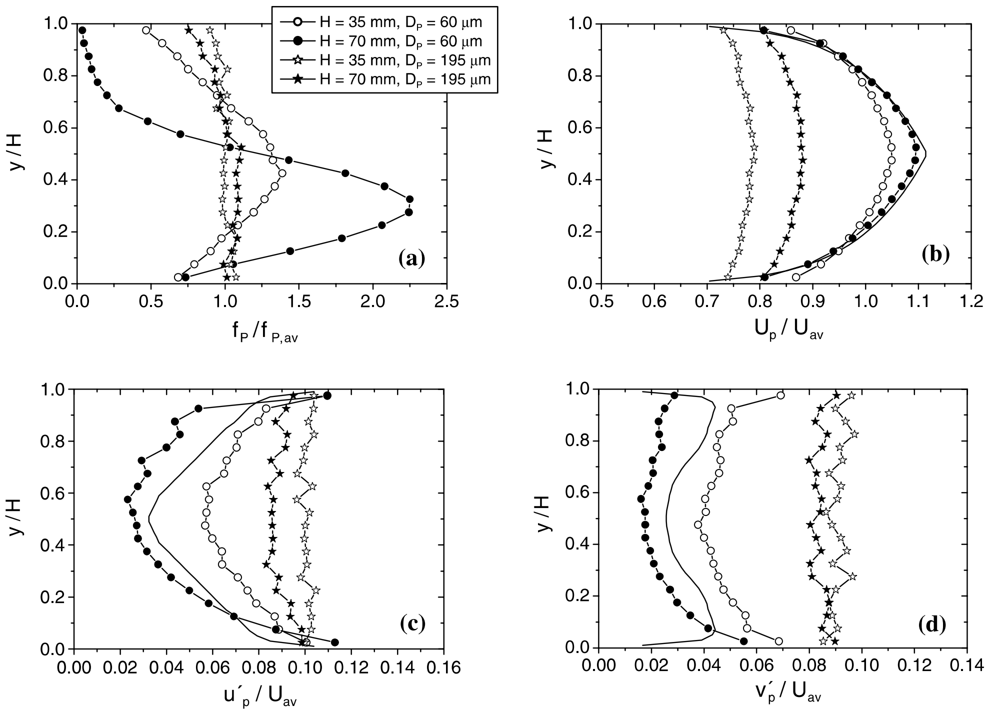

Fig. 6. Calculated profiles of particle phase properties in the developed region of the channel, comparison of results for different channel height ($H = 35$ and 70 mm) and particle diameter ($D_P = 60$ and 195 μm): (a) normalised particle mass flux; (b) horizontal velocity component; (c) horizontal rms-velocity; (d) vertical rms-velocity (closed lines indicate the prescribed gas velocities, with inter-particle collisions, with wall roughness HR, $H = 70$ mm, $\eta = 1.0$, $U_{av} = 18$ m/s).

the fluctuating motion is observed up to a mass loading of about 1.0. With further increasing loading a saturation occurs similarly to the narrow channel.

The above results clearly demonstrate, that for an increase of channel height the particle motion becomes less strongly wall collision dominated. As a consequence their velocity fluctuation is considerably reduced, especially in an intermediate size range (i.e. very small particles are dominated by turbulence and very large particles governed by inertia). Inter-particle collisions however, are also important for wider channels and the same phenomena are observed as described for the smaller channel.

4. Comparison of measurement and calculation

A reliable modelling of the involved physical processes is essential for a good numerical prediction of the two-phase flow in consideration. The results presented above and by (Sommerfeld, 2003) revealed the importance of the phenomena wall collisions, wall roughness, and inter-particle collisions. For validating the model developments and improvements, additionally numerical predictions were performed in accordance with detailed experiments conducted by Kussin and Sommerfeld (2002) using PDA. In all these calculations two-way coupling effects are neglected

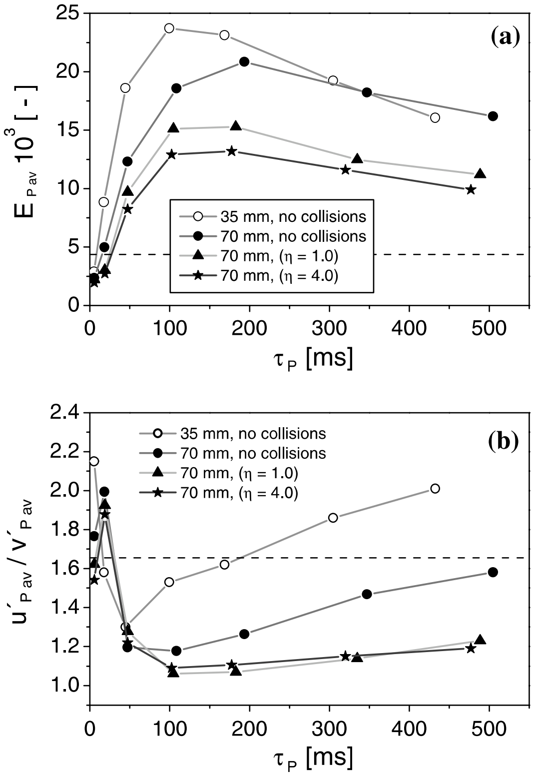

Fig. 7. Calculated averaged properties of particle fluctuating velocity across the channel, comparison of results for different channel height ($H = 35$ and 70 mm): (a) averaged fluctuating energy; (b) ratio of fluctuating velocity components (dashed line: gas-phase fluctuating properties, $U_{av} = 18$ m/s).

since they are of minor importance compared to the other effects as demonstrated by Lain et al. (2002). Furthermore, these calculations were performed by adjusting the profile of the stream-wise gas velocity in order to fit the measurements. The profiles of the gas-phase velocity fluctuations were again taken from Laufer (1950) and adjusted according to the considered mean gas velocity.

In the first case, spherical glass beads with a mean number diameter of 100 μm ($\rho_P = 2500$ kg/m^3) conveyed with an average gas velocity of 19.7 m/s at a mass loading of $\eta = 1.0$ are considered. The effect of wall roughness is emphasised by comparing the calculated particle phase properties for both situations (i.e. smooth and rough wall) with the measurements obtained by PDA in Fig. 8. In both cases inter-particle collisions are considered. The agreement of the calculations considering wall roughness is found to be very good for all the particle phase properties. Somewhat larger differences are only observed for the stream-wise mean velocity which is slightly underpredicted over the entire channel. The deviation from the measurements is between 2% and 5%. Calculations without wall roughness (i.e. smooth wall), but with inter-particle collisions show the expected trends. The stream-wise component of the particle velocity is considerably over-predicted due to the reduction of wall collision frequency and the associated decreasing particle momentum loss and as a consequence of the reduced lateral dispersion the velocity profile becomes more bulged without roughness. The profile of the normalised particle concentration

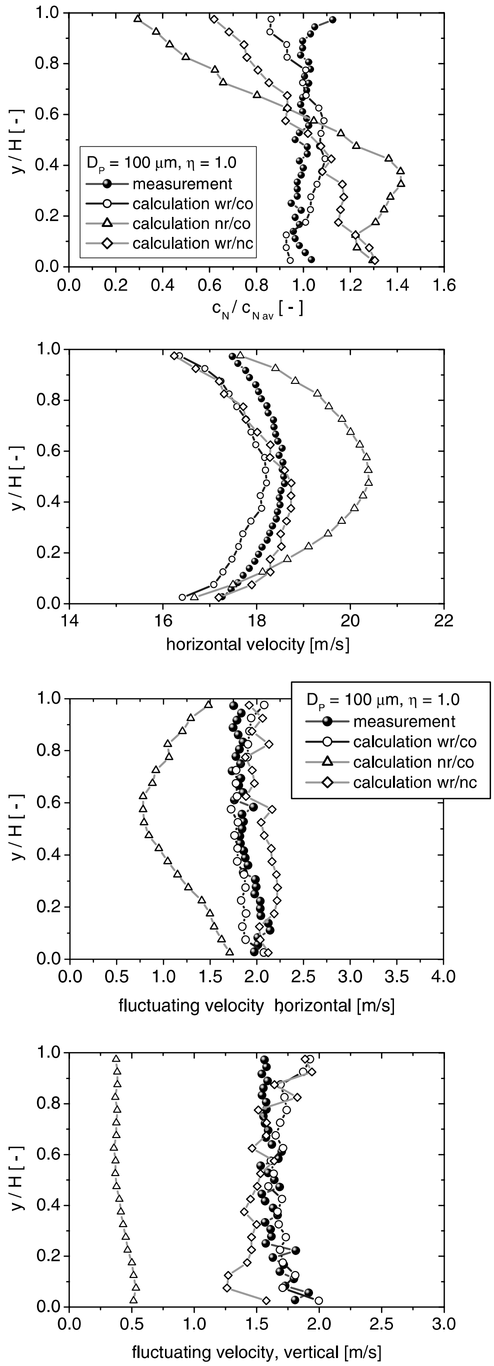

Fig. 8. Comparison of calculations using different boundary conditions with experiments ($H = 35$ mm, $U_{av} = 19.7$ m/s, $D_P = 100$ μm, $\eta = 1.0$), (nr: no roughness, wr: with roughness HR, nc: no collisions, co: inter-particle collisions, high roughness).

reveals a strong sedimentation of the particles as a result of gravity. The fact that the maximum in the particle concentration is not near the bottom is solely the result of inter-particle collisions. Moreover, neglecting wall roughness results in a considerable under-estimation of the fluctuating velocities of the particle phase, which is most pronounced for the vertical component as shown previously (Sommerfeld, 2003).

The calculations with wall roughness but without inter-particle collisions show a stronger sedimentation of the particles in the profiles of the normalised particle concentration compared to the case with collisions. Since there is no momentum loss due to inter-particle collisions, also the stream-wise velocity of the particle becomes higher than for the case with collisions in the lower part of the channel. The horizontal component of the particle rms-velocity is enhanced and the vertical component is reduced when neglecting particle collisions. This demonstrates clearly the isotropisation effect of inter-particle collisions.

An interesting phenomenon is observed when inspecting the profiles of the vertical component of the particle mean velocity (Fig. 9). Without roughness this velocity component is almost zero as expected for a developed flow. However, with roughness the profile shows a Z-shaped velocity distribution in the range ±0.2 m/s. Near the lower wall a high positive transverse velocity is resulting from the so-called shadow effect whereby the average transverse rebound velocity is higher than the impact component (Sommerfeld and Huber, 1999). Near the upper wall of course a negative mean transverse velocity is found. In the region between about 0.1 and 0.9 normalised wall distances the transverse mean velocity is directed towards the walls. In the experiment a very similar profile was found and the agreement with the calculations is very good. Since this result implies still some net transport of the particles it may be concluded, that the flow is not yet fully developed. Therefore, also a calculation with a much longer channel of 12 m was performed. However, the result is quite similar to that for the short channel with wall roughness. The comparison of the normalised concentration profiles for the different calculations revealed that the observed magnitude of the transverse mean velocity only results in some minor changes (not shown here). The above described phenomena were also found for other particle sizes in a

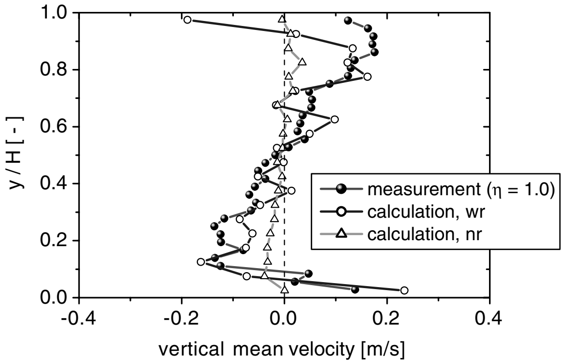

Fig. 9. Comparison of calculations using different boundary conditions with experiments for the transverse particle mean velocity ($H = 35$ mm, $U_{av} = 19.7$ m/s, $D_P = 100$ μm, $\eta = 1.0$), (nr: no roughness, wr: with roughness HR, with inter-particle collisions, high roughness).

situation with wall roughness. Hence it seems that although the flow development is improved by wall roughness, a fully developed situation requires a longer distance.

The effect of inter-particle collisions on the particle phase properties is additionally demonstrated for a case with a gas-phase bulk velocity of 14.25 m/s and a wall with lower roughness as shown previously (Sommerfeld, 2003). For such a situation one will expect a more pronounced gravitational settling for the 100 μm particles. This is illustrated in Fig. 10(a) for a calculation of the normalised particle concentration obtained with inter-particle collisions in comparison with measurement at a mass loading of $\eta = 0.1$. For these conditions an almost linear increase of the particle concentration towards the bottom of the channel is found. The agreement of the calculations with measurements is very good. For a considerable higher mass loading ($\eta = 0.9$) inter-particle collisions have a strong effect on the profile of particle concentration (Fig. 10(b)). The high particle concentration near the bottom results in an enhancement of the inter-particle collisions whereby the particles are flanged out of the dense bottom region and the maximum in particle concentration is shifted upward. The agreement between the numerical results and the measurements is found to be reasonable good. The lower measured concentration values near the bottom may be caused by a bias effect in the measurements originating from a stronger absorption of the scattered light at high mass loading, whereby the validated number of particle samples decreases with increasing optical path length, namely from the top to the bottom of the channel.

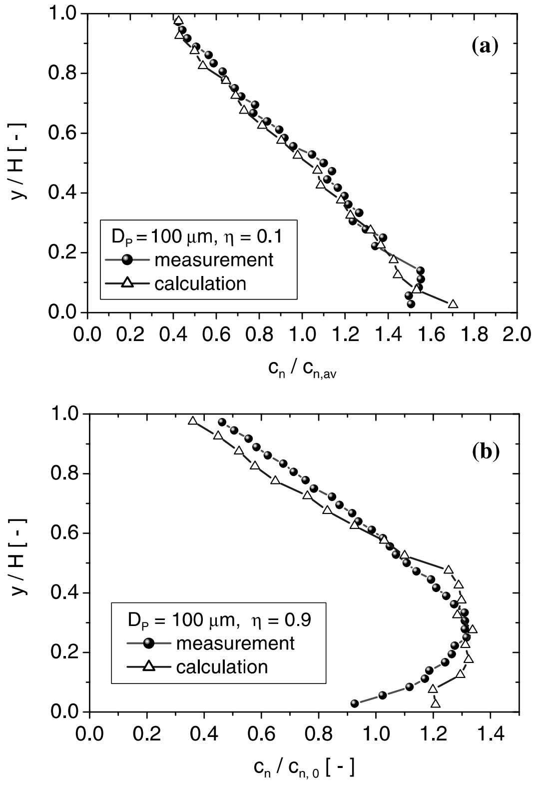

Fig. 10. Comparison of profiles for the normalised particle number concentration obtained by calculations with inter-particle collisions and experiments for the low roughness case ($U_{av} = 14.25$ m/s, $D_P = 100$ μm), (a) $\eta = 0.1$, (b) $\eta = 0.9$.

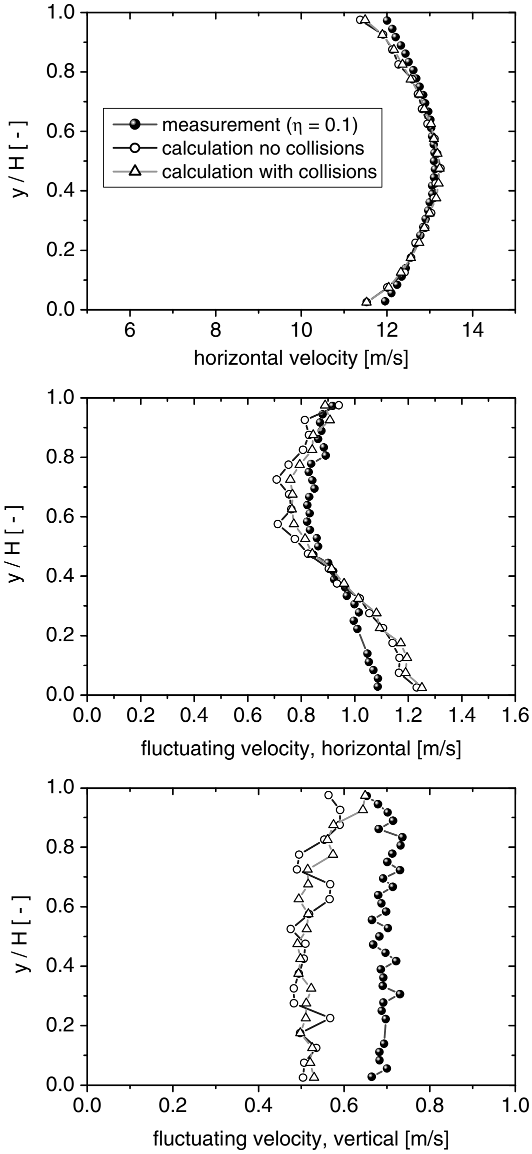

Fig. 11. Comparison of calculations without and with inter-particle collisions and the experiments for the low roughness case ($H = 35$ mm, $U_{av} = 14.25$ m/s, $D_P = 100$ μm, $\eta = 0.1$).

For completeness, also the calculated mean and fluctuating velocities of the particles in the case of a mass loading of $\eta = 0.1$ are compared with measurements in Fig. 11. The mean velocity profile is captured fairly good by the numerical results. However, some larger discrepancies are revealed for the particle phase fluctuations. The stream-wise component is slightly over-predicted near the bottom of the channel and under-predicted in the upper half of the channel. On the other hand the shape of the profile is captured very well, namely near the bottom the fluctuation velocity is considerably higher than near the upper wall of the channel. This is the result of the saltating motion of particles as indicated previously by the particle trajectories (Sommerfeld, 2003). The vertical component of the particles fluctuating velocity is considerably under-predicted for this case which is supposed to be a bias effect in the measurements and was also observed in a number of other cases. The comparison of calculations without and with inter-particle collisions reveals only smaller differences in the fluctuating components. A slight enhancement is however obvious for the stream-wise component of the particle fluctuation.

The differences between experiment and calculation explained above, become also clear when comparing the velocity distributions at two measurement positions close to the bottom of the channel (Fig. 12). The distributions for the stream-wise particle velocity are captured fairly well and also reveal the slight under-prediction of the rms-value near the bottom. A kind of bimodal velocity distribution, indicating the momentum loss of the particles due to wall collisions, is observed in the numerical calculations, but not in the experiment. The distributions of the transverse particle velocity exhibit no bimodal shape as one would expect (Fig. 13), since particles

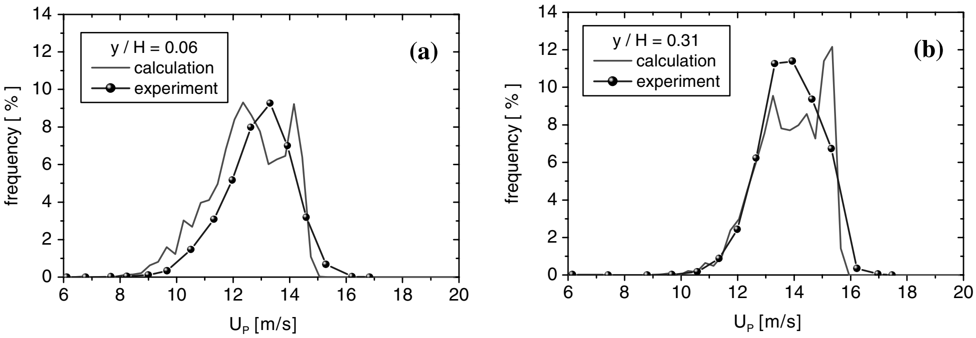

Fig. 12. Comparison of the calculated and measured velocity distributions in the stream-wise direction at two vertical positions for low roughness and with inter-particle collisions ($H = 35$ mm, $U_{av} = 14.25$ m/s, $D_P = 100$ μm, $\eta = 0.1$): (a) $y/H = 0.06$, (b) $y/H = 0.31$.

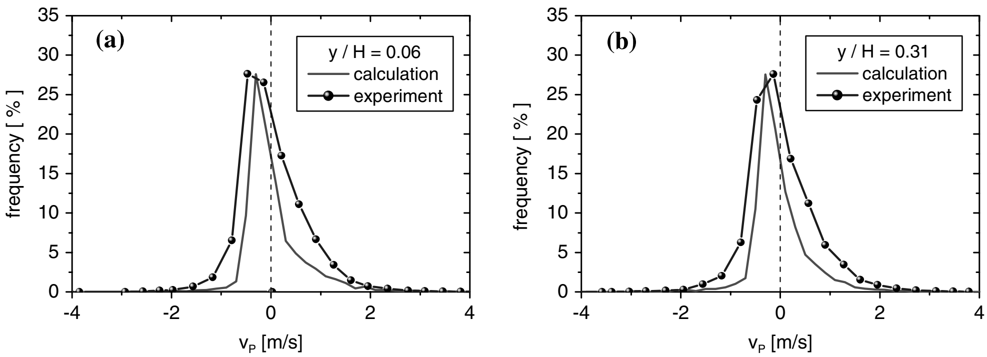

Fig. 13. Comparison of the calculated and measured velocity distributions in the transverse direction at two vertical positions for low roughness and with inter-particle collisions ($H = 35$ mm, $U_{av} = 14.25$ m/s, $D_P = 100$ μm, $\eta = 0.1$): (a) $y/H = 0.06$; (b) $y/H = 0.31$.

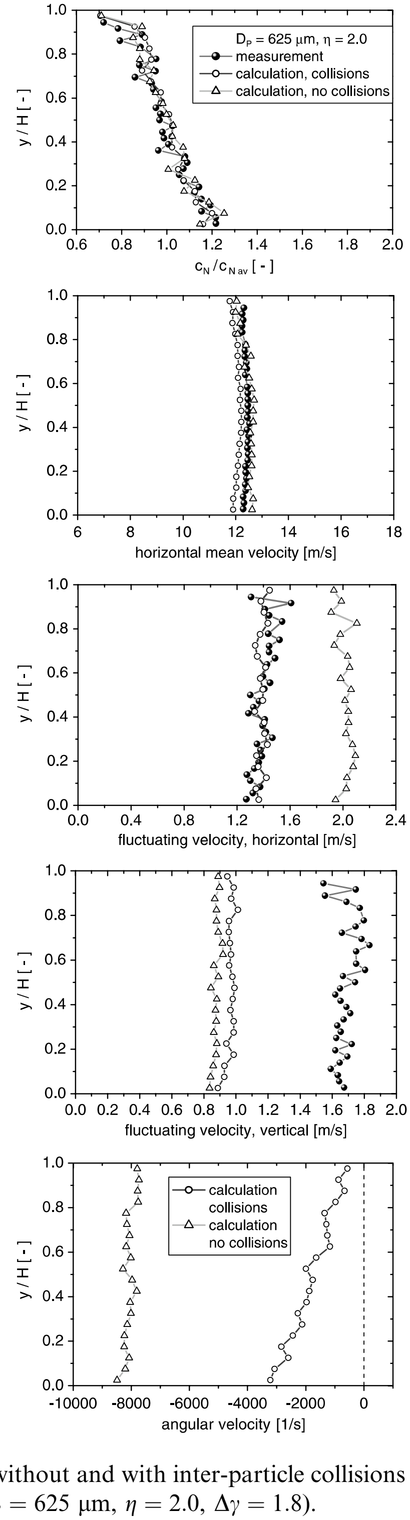

Fig. 14. Comparison of calculations without and with inter-particle collisions and the experiments for a low roughness case ($H = 35$ mm, $U_{av} = 19.7$ m/s, $D_P = 625$ μm, $\eta = 2.0$, $\Delta\gamma = 1.8$).

are sampled moving towards the wall and being rebound. Instead the velocity is distributed around zero with a steep increase on the negative side and a more continuous decay on the positive side. This is similar for both, the calculations and the experiment. As a result of the measured higher rms-values also the velocity distributions are wider in the experiment than in the computations.

Eventually, a comparison of calculation and measurement is also performed for spherical glass beads with a diameter of 625 μm (Fig. 14). It should be noted that for this case the wall roughness was between the high and low roughness values given previously (Sommerfeld, 2003). Hence, a roughness angle of $\Delta\gamma = 1.8°$ was found to be suitable for this case. It is expected that such large particles are dominantly affected by wall- and inter-particle collisions. The comparison with the experiment shows excellent agreement if inter-particle collisions are taken into account for the normalised concentration, the stream-wise mean and the associated fluctuating velocity. The transverse fluctuating velocity of the particles however, is found to be considerably higher in the measurements. When neglecting inter-particle collisions a slight decrease of the transverse fluctuating component is found, whereas the mainstream component becomes considerably higher. This again reveals the isotropisation effect of inter-particles collisions. As one would expect the horizontal component of the particle mean velocity is slightly enhanced when neglecting inter-particle collisions. Finally it is demonstrated that the particle angular mean velocity is strongly affected by inter-particle collisions (Fig. 14). Collisions with the lower wall are prevailing when neglecting inter-particle collisions and the mean angular velocity is almost constant across the channel with values around −8000 1/s. Due to particle collisions, the particle fluctuation in the transverse direction is slightly enhanced and the lateral dispersion is improved. This increases the probability of particles hitting the upper wall, whereby the contribution of positive values for the angular velocity increases and hence, the mean values are drastically increased across the channel. Unfortunately, it was not possible to measure the particle angular velocity.

The comparison of the calculations with the experiments revealed that the agreement is satisfactorily for most cases, indicating that the important transport phenomena, namely wall collisions, wall roughness, and inter-particle collisions are properly described by the developed models.

5. Conclusion

Based on numerical calculations using the Lagrangian approach including appropriate models for wall- and inter-particle collisions, the influence of both phenomena on integral properties averaged over the channel height was demonstrated. Wall roughness has a dramatic effect on the average transport velocity of the particles which is reduced with increasing degree of roughness. This of course has a consequence for the pressure loss in pneumatic conveying. Additionally, the fluctuating energy of the particles is enhanced by wall roughness. Especially for a rough wall inter-particle collisions again reduce the fluctuating motion in average due to the associated dissipation of energy.

Also the angular particle velocity is strongly affected by both wall collisions including roughness and inter-particle collisions. This influence is mainly associated with the modification of the particles lateral dispersion and the relative importance of the wall collision frequency with the upper and the lower wall. For inertial particles, which perform a saltating motion, the angular velocity has high negative values due to preferential collisions with the lower wall. While with roughness the probability of hitting the upper wall increases the contribution of positive angular velocities, whereby the mean value is increased over the entire channel. Similar effects are observed due to inter-particle collisions.

Numerical calculations for a channel with a larger height revealed that the importance of wall collisions and hence wall roughness decreases, especially for smaller particles. This results in higher stream-wise mean velocities of the particles and a reduction in the fluctuating velocities. With increasing particle inertia the behaviour of the particle motion in a narrow or wider channel becomes roughly the same and wall collisions are the dominating transport effect.

The comparison of the calculations with detailed measurements using PDA for different conveying velocity, particle sizes, and mass loading showed in general an excellent agreement, indicating a correct modelling of the involved transport processes, namely particle–wall collisions and inter-particle collisions. The isotropisation of the particle phase fluctuation due to inter-particle collisions was clearly demonstrated.

Acknowledgements

The research project is financially supported by the Deutsche Forschungsgemeinschaft. This support under contract number So 204/12-1 and 2 is gratefully acknowledged.

References

Adam, O., 1960. Untersuchungen über die Vorgänge in feststoffbeladenen Gasströmungen. Forschungsberichte des Landes Nordrhein-Westfalen. Westdeutscher Verlag, Köln.

Kussin, J., Sommerfeld, M., 2002. Experimental studies on particle behaviour and turbulence modification in horizontal channel flow with different wall roughness. Experiments in Fluids 33, 143–159.

Lain, S., Kussin, J., Sommerfeld, M., 2002. Experimental studies and modelling of four-way coupling in particle-laden horizontal channel flow. Int. J. Heat and Fluid Flow 23, 647–656.

Laufer, J., 1950. Investigation of turbulent flow in a two-dimensional channel. National Advisory Committee for Aeronautics, NACA Technical Note 2123.

Sommerfeld, M., 1995. The importance of inter-particle collisions in horizontal gas–solid channel flows. In: Stock, D.E. et al. (Eds.), Gas-Particle Flows, ASME Fluids Engineering Conference, Hiltons Head, USA, ASME, FED-Vol. 228, pp. 335–345.

Sommerfeld, M., 2003. Analysis of collision effects for turbulent gas-particle flow in a horizontal channel: Part I. Particle transport. Int. J. Multiphase Flow, 29, doi:10.1016/S0301-9322(03)00031-4.

Sommerfeld, M., Huber, N., 1999. Experimental analysis and modelling of particle–wall collisions. Int. J. Multiphase Flow 25, 1457–1489.

Tanaka, T., Tsuji, Y., 1991. Numerical simulation of gas–solid two-phase flow in a vertical pipe: On the effect of inter-particle collision. In: Stock, D.E., Tsuji, Y., Jurewicz, J.T., Reeks, M.W., Gautam, M. (Eds.), Gas–Solid Flows. ASME, FED-Vol. 121, pp. 123–128.

Tsuji, Y., Morikawa, Y., Tanaka, T., Nakatsukasa, N., Nakatani, M., 1987. Numerical simulation of gas–solid two-phase flow in a two-dimensional horizontal channel. Int. J. Multiphase Flow 13, 671–684.

Yilmaz, A., Levy, E.K., 2001. Formation and dispersion of ropes in pneumatic conveying. Powder Technology 114, 168–185.