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## MODELING OF ANISOTROPIC PARTICLE MOTION IN TURBULENT CHANNEL FLOW AND COMPARISON WITH EXPERIMENTS

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### ABSTRACT

The motion of inertial particles suspended in a turbulent channel flow is numerically simulated by means of a new dispersion model based on accurate modelling of the directional dependence of the fluid Lagrangian time scales. The continuum phase is described by a non-linear low-Reynolds  $k$ - $\varepsilon$  model, whereas the dispersed phase motion is predicted by a Lagrangian stochastic method aimed at taking the non-homogeneity and the anisotropy of turbulence into account. The fluid Lagrangian time scales in each direction are assessed following a recent proposal supported by channel flow DNS computations. The integral time scales of the fluid seen by the particles are then estimated in taking the inertia and crossing trajectory effects into account. The numerical predictions (particle and fluid statistical quantities) obtained using this model are compared to previously available formulations of the Lagrangian time scales and to recent experimental data from the literature about the motion of small glass beads in a turbulent vertical channel flow. The new Lagrangian time scale formulation is found to yield very satisfactory results compared to the measurements.

### INTRODUCTION

In this work, an improved Eulerian-Lagrangian numerical model is proposed to describe the transport of inertial particles (solid particles or droplets) in a turbulent shear flow. Results are presented and compared with experiments in the case of a fully developed gas-solid turbulent channel flow. The fluid flow is described by an anisotropic  $k$ - $\varepsilon$  low Reynolds closure model. The trajectories of a large number of solid particles injected in the gas flow are numerically tracked in the computational domain. As is well known, the particle equations of motion involve the instantaneous velocity of the fluid at the particle location, or velocity of the fluid seen by the particle.

Two main ways of evaluating the instantaneous fluid velocity at the particle location have been developed in the literature. In the so-called eddy interaction models [1-2] it is considered that the particle successively crosses several random discrete eddy structures, each of them defined by its lifetime, influence zone and intensity. Such models, which have been widely developed and discussed, are able to render complex physical phenomenon such as the crossing trajectory effect which reduces the particle dispersion in case of non-zero mean relative velocity, and the associated continuity effect which makes the dispersion in the direction of the drift velocity decrease less than in the other two directions, however it still cannot handle anisotropy or inertia effects properly. A more recent family of models involves first-order auto-regressive stochastic processes to correlate the fluid velocity seen by a particle at its new location with the fluid velocity at the previous position. Among such models, two-step methods have been developed during the past decade [3-7], where the new velocity fluctuation is predicted by means

of a first-order time series for the fluid particle path, followed by a spatial step which is written in a similar manner using a given Eulerian length scale. The drawbacks of such two-step methods, as identified and discussed by Pozorski and Minier [8], are due to the inconsistency of the spatial step which results mainly in incorrect prediction of the kinetic energy of the fluid seen and of the inertia effect.

The model in use in this study is a one-step correlation model that requires the evaluation of the integral time scales of the fluid seen by the particle in each direction,  $T_i^*$ , in order that the instantaneous fluid velocity seen at time level  $t$  can be directly predicted from the fluid velocity seen at time level  $t+\Delta t$ , tracking the same discrete particle [9-10]. Unfortunately, there is no general expression so far to evaluate such integral scales, which are only available in some limited cases by means of Direct Numerical Simulation. Even though various methods have been suggested to estimate the time scales of the fluid seen, the proposed correlations are still restricted to homogeneous isotropic turbulence. Wang and Stock [11], as well as Pozorski and Minier [8] or Derevich [12], proposed expressions of  $T^*$  accounting for the inertia effect, depending on  $T_L$  and  $T_{mE}$ , the fluid Lagrangian and moving Eulerian integral time scales, respectively (leaving out the index due to the isotropy assumed by these authors). The crossing trajectory effect can be introduced in such models following the principle of Csanady's derivation [11,13]. Making the assumption that these expressions, validated only in the case of isotropic homogeneous turbulence, can be extended to shear flow cases, the fluid time scales in each direction,  $T_{Li}$  and  $T_{mEi}$ , are the remaining unknowns to be evaluated.

The main purpose of this work is therefore to assess the performance of an anisotropic dispersion model based on a recent proposal for the prediction of the directional dependence of the fluid Lagrangian integral time scales [14]. This model is compared to the anisotropic formulation used by Berlemont *et al.* [3] or Zhou and Leschziner [6] and to an isotropic model. Numerical computation of statistical quantities using these three formulations are then confronted to the experimental data by Khalitov and Longmire [15] resulting from the study of the motion of small glass beads in a fully developed turbulent vertical channel flow.

## MODEL DESCRIPTION

### Fluid phase

The gas flow is calculated by means of a Non Linear Eddy Viscosity Model (NEVM, Rokni and Sunden [16]), so that turbulence anisotropy is taken into account. In order to provide more precision in the near wall region where the viscosity effects have to be taken into account, the Low-Reynolds model elaborated by Myong and Kasagi [17] has been selected here and implemented in the Eulerian description of the fluid phase flow.

### Discrete phase modelling

Trajectories of spherical, rigid particles are computed through integration of the particle equations of motion along the channel. Due to particle-wall interactions, which are not supposed to be frictionless, particles may be subjected to significant rotational motion which has to be taken into account in expressing the particle-fluid interactions. The particle motion is therefore described by a set of six scalar equations (linear and angular momentum conservation). Besides the quasi-stationary drag force, which is expressed according to usual standard correlations for the drag coefficient in terms of the sphere Reynolds number, particles are experiencing a torque and a lift force which may be of significant importance, particularly for large particles. The lift force is calculated through the correlation proposed by Oesterlé and Bui Dinh [18], valid for a large range of Reynolds numbers, and the torque is expressed according to the correlation of Dennis *et al.* [19]. Owing to the high particle-to-fluid density ratio, non-stationary contributions to the drag force, such as history force, added mass force and displaced force can be neglected.

In case of particle-wall collision, the new components of the translational and rotational velocities are calculated as a function of the velocity components before collision using the linear and angular momentum equations and Coulomb's law during the very short contact duration. The parameters needed for the processing of collisions are the coefficient of restitution  $e$  and the coefficients of static and kinetic friction  $f$  and  $f_0$ . Additionally, in order to take into account the effects of wall roughness and possible non-sphericity of particles, the virtual wall model proposed by Sommerfeld [20] is used, where the actual wall is replaced by a virtual wall whose inclination is selected from a centered Gaussian distribution with given standard deviation  $\sigma_r$ . The so-called shadow effect is taken into account in order to avoid any unphysical rebound.

The particle-to-air mass loading in the experiments of Khalitov and Longmire [15] being of order 10%, the collisions between particles are not considered in this study.

For similar reasons, the effect of the dispersed phase upon the fluid flow can be neglected, so that the only coupling effect is the fluid-to-particle one, *i.e.* one-way coupling. After the Eulerian computation of the fluid flow field, the Lagrangian step is performed by tracking a large number of particles, with the fluctuating quantities of the fluid flow being calculated at each particle location by means of the dispersion model described below, using the data provided by the Eulerian calculation.

### Dispersion model

As the fluid-particle interactions involve the instantaneous velocity of the fluid at the particle location, which is not available from RANS modelling of the turbulent fluid flow, a reconstruction method is necessary in order to properly build the fluctuating velocity in accordance with the given first and second-order statistical moments of the turbulence. As mentioned above, a stochastic one-step method is used to predict the fluid velocity seen by a discrete particle at time  $t$  in terms of the value of the fluid velocity at time  $t + \Delta t$  and at the previous location of the same solid particle, following the first-order autoregressive process :

$$u_{i_n}^* = u_{i_{n-1}}^* e^{-\Delta t/T_i^*} + \psi_{i_n} \quad (1)$$

where  $u_{i_n}^*$  is the  $i$ -component of the velocity fluctuation of the fluid at the discrete particle location at time  $t = n\Delta t$ ,  $T_i^*$  is the integral time scale of the fluid seen in the  $i$ -direction, and the  $\psi_{i_n}$  are independent centered Gaussian variables. In order to take turbulence anisotropy into account and to be consistent with the fluid Reynolds stress tensor, the components of the covariance matrix of the white noise disturbances  $\psi_{i_n}$  have to be linked with the values of the Reynolds stresses given by the Eulerian computational step :

$$\langle \psi_{i_n} \psi_{j_n} \rangle = \left( 1 - \exp \left( -\Delta t \left( \frac{1}{T_i^*} + \frac{1}{T_j^*} \right) \right) \right) \langle u_i u_j \rangle, \quad (2)$$

under local homogeneity assumption in order that the process be stationary. A simple procedure to generate such random numbers  $\psi_{i_n}$  is to select  $\psi_{1_n}$  from a normal p.d.f. with zero mean and variance  $\langle \psi_{1_n}^2 \rangle = (1 - \exp(-2\Delta t/T_1^*)) \langle u_1^2 \rangle$ , and to build  $\psi_{2_n}$  and  $\psi_{3_n}$  by  $\psi_{2_n} = a_0\phi + a_1\psi_{1_n}$  and  $\psi_{3_n} = b_0\chi + b_1\psi_{1_n} + b_2\psi_{2_n}$ , where  $\phi, \chi$  are independent Gaussian variables with zero mean and variance unity, and the coefficients  $a_k, b_k$  are deduced from Eq. (2).

In order to avoid any spurious drift of the fluid particles towards the low turbulence intensity regions, the formulation by Eq. (1) has to be corrected in case of non homogeneous turbulence by taking the variations of the fluid Reynolds stresses into account [21-22]. In the present channel flow configuration, denoting by  $x, y, z$  the streamwise, wall-normal and spanwise directions, respectively, the  $y$ -derivatives of the fluid Reynolds stresses are involved, leading to the following final expressions for the fluid velocity generation process in each direction :

$$u_{x_n}^* = u_{x_{n-1}}^* \exp\left(-\frac{\Delta t}{T_x^*}\right) + \psi_{x_n} + \frac{\partial \langle u_x u_y \rangle}{\partial y} T_x^* \left(1 - \exp\left(-\frac{\Delta t}{T_x^*}\right)\right) \quad (3)$$

$$u_{y_n}^* = u_{y_{n-1}}^* \exp\left(-\frac{\Delta t}{T_y^*}\right) + \psi_{y_n} + \frac{\partial \langle u_y^2 \rangle}{\partial y} T_y^* \left(1 - \exp\left(-\frac{\Delta t}{T_y^*}\right)\right) \quad (4)$$

$$u_{z_n}^* = u_{z_{n-1}}^* \exp\left(-\frac{\Delta t}{T_z^*}\right) + \psi_{z_n} \quad (5)$$

The integral Lagrangian time scales  $T_i^*$  of the fluid seen by the discrete particles are evaluated following the proposals of Wang and Stock [11], which may yield acceptable estimates even in case of non-homogeneous anisotropic flow, provided that the fluid Lagrangian time scales  $T_{Li}$  and moving Eulerian time scales  $T_{mEi}$  (measured in a frame moving with the mean fluid velocity) are properly assessed in terms of the  $y$ -location along the channel height, as described later. The first step of the calculation is the evaluation of the integral time scales under the hypothesis that no external force is acting, by means of the following expression :

$$T_{0i}^* = T_{mEi} \left(1 - \left(1 - \frac{T_{Li}}{T_{mEi}}\right) (1 + St_i)^{-0.4(1+0.01St_i)}\right) \quad (6)$$

where the inertia effect is taken into account through the particle Stokes numbers  $St_i = \tau_p / T_{mEi}$ ,  $\tau_p$  being the particle relaxation time. Then, the crossing trajectory effect, which is due to the gravity induced mean relative velocity  $V_r$  (directed in the streamwise direction  $x$ ), is introduced by expressing the time scales  $T_x^*$ ,  $T_y^*$ ,  $T_z^*$  in terms of  $T_{0i}^*$  and  $V_r$ , still following Wang and Stock [11] :

$$T_x^* = T_{0x}^* \left(1 + \left(\frac{T_{0x}^* V_r}{L_f}\right)^2\right)^{-1/2} \quad (7)$$

$$T_{y,z}^* = T_{0y,z}^* \left[ \left(1 + \left(\frac{T_{0y,z}^* V_r}{L_f}\right)^2\right)^{1/2} - \frac{T_{0y,z}^* V_r}{2L_f} \right] \left(1 + \left(\frac{T_{0y,z}^* V_r}{L_f}\right)^2\right)^{-1/2} \quad (8)$$

where  $L_f$  is the longitudinal integral length scale defined here by  $L_f = \sqrt{\langle u_x^2 \rangle} T_{mEx}$ .

At that point the Eulerian and Lagrangian time scales of the fluid in each direction,  $T_{mEi}$  and  $T_{Li}$ , are the key quantities to evaluate, and from the quality of this evaluation will depend the accuracy of the particle motion description. Several models have been developed in the literature to estimate the Lagrangian time scales in anisotropic turbulent flows and to account for the directional dependency of these quantities. The available proposals are :

$$T_{Lij} \cong C_L \frac{\langle u_i u_j \rangle}{\varepsilon} \quad (9)$$

with  $C_L = 0.2$  to  $0.25$ , according to Berlemont *et al.* [3] or Zhou and Leschziner [6], who normalized the velocity

correlations by the rms (root mean square) velocities in directions  $i$  and  $j$  (so that it is not surprising to obtain negative values for the off-diagonal time scales), or, alternatively :

$$T_{Lij} \cong C_L \frac{\langle u_i^2 \rangle + \langle u_j^2 \rangle}{2\varepsilon} \quad (10)$$

according to Burry and Bergeles [5], who normalized the velocity correlations by the corresponding Reynolds stress. In Eq. (9)-(10),  $\varepsilon$  denotes the dissipation rate of turbulent kinetic energy.

Besides the lack of any physical ground (except dimensional arguments), the main drawback of such proposals is the assumed symmetry in  $i$  and  $j$ , which is not correct in turbulent shear flows. From any of the above expressions, the ratios of the streamwise and spanwise Lagrangian integral scales to the wall-normal scale would be :

$$\frac{T_{Lx}}{T_{Ly}} = \frac{\langle u_x^2 \rangle}{\langle u_y^2 \rangle}, \quad \frac{T_{Lz}}{T_{Ly}} = \frac{\langle u_z^2 \rangle}{\langle u_y^2 \rangle} \quad (11)$$

Contrary to such empirical estimates, in the present approach we make use of the recent proposal by Rambaud *et al.* [14] for the prediction of the streamwise and spanwise Lagrangian time scales in terms of the wall-normal one. This model, supported by comparison with available channel flow LES and DNS computations, was shown to yield significant improvement compared to the generally used empirical expressions (11). In the suggested formulation, the ratios of the streamwise and spanwise time scales to the wall-normal one are expressed in terms of the local Reynolds stress tensor components by :

$$\frac{T_{Lx}}{T_{Ly}} = \Psi \frac{\langle u_x^2 \rangle}{\langle u_y^2 \rangle}, \quad \frac{T_{Lz}}{T_{Ly}} = \Psi \frac{\langle u_z^2 \rangle}{\langle u_y^2 \rangle}, \quad (12)$$

where the factor  $\Psi$  is defined by :

$$\Psi = \frac{1 + \langle u_x u_y \rangle^2 \langle u_x^2 \rangle^{-2}}{1 + \langle u_x u_y \rangle^2 \langle u_y^2 \rangle^{-2}} \quad (13)$$

In order to estimate the wall-normal Lagrangian time scale  $T_{Ly}$ , it is possible to use the empirical formulation proposed by Ushijima and Perkins [23], who started from the expression arising from the Langevin model in stationary homogeneous isotropic turbulence,  $T_L = 4k/(3C_0\varepsilon)$ , and used a wide range of experimental and numerical results to propose an empirical expression of the "constant"  $C_0$  as a function of the wall distance in order to obtain a more accurate evaluation of  $T_{Ly}$  in pipe or channel flows. Another way is to make use of the eddy viscosity based expression of  $T_{Ly}$ . This method, which will be applied in the following, lies on the identification of the eddy viscosity  $\nu_t$  with the long time turbulent diffusivity of Taylor's theory, leading to  $\nu_t = \langle u_y^2 \rangle T_{Ly}$  and to the following expression for  $T_{Ly}$  :

$$T_{Ly} = -\frac{\langle u_x u_y \rangle}{\langle u_y^2 \rangle d\langle U_x \rangle / dy} \quad (14)$$

where  $\langle U_x \rangle$  is the local mean velocity in the channel. From comparison with DNS and LES results, it has been shown recently by Rambaud *et al.* [14] that the predictions of  $T_{Ly}$  by means of Eq. (9) or (10) are far from being satisfactory, and that the only acceptable estimates of  $T_{Ly}$  are by the formulation of Ushijima and Perkins [23] or by the eddy viscosity based expression given by Eq. (14).

Starting from these estimations of the Lagrangian time scales, the moving Eulerian time scales are deduced by simply considering a fixed and constant value of the ratios  $\beta_i = T_{Li}/T_{mEi}$ , namely  $\beta_i \cong 0.6$ , which seems to be an acceptable estimate according to available LES and DNS results in channel flows [14, 24].

In the following section, we investigate the impact of the new anisotropic formulation of the Lagrangian time scales by means of comparisons between experimental data and numerical predictions obtained from various models.

## NUMERICAL RESULTS AND DISCUSSION

As mentioned in the introduction part, the simulation results are compared with the experimental results of Khalitov and Longmire [15], who presented many results obtained in a fully developed vertical channel flow loaded with small solid particles. The fluid and particle velocities were measured simultaneously by two-phase PIV. The channel dimensions were  $h = 7.5\text{mm}$  and  $l = 110h$  for the half-width and the dynamic length respectively, and the depth dimension was sufficiently large to avoid wall proximity effects in that direction and to suppose a two-dimensional flow. Five sets of monodisperse spherical solid particles were tested with mean diameter  $d_p$  ranging from  $20\text{ }\mu\text{m}$  to  $160\text{ }\mu\text{m}$ . The particle density was  $2500\text{ kg m}^{-3}$ . The fluid centerline velocity was equal to  $10\text{ ms}^{-1}$ , the Reynolds number based on this velocity and the channel half-width  $h$  was  $Re_h = 4500$ , and the estimated Stokes numbers based on integral time scale at the channel center varied in the range  $0.2-10$ . As already mentioned, the particle-to-air mass loading was about 10% for each experiment, so that the particles did not significantly affect the gas mean and rms velocity profiles. Accordingly, the present numerical simulations have been performed using one-way coupling.

To ensure fully-developed flow conditions, periodic boundary conditions are used for the trajectory calculations between the inlet and the outlet section of the channel. To improve the description of the gas flow in the near wall region by means of the Eulerian model, a stretched grid is adopted in the wall-normal direction, following a logarithmic distribution law with 50 nodes along the channel half-width, the first node being located at  $y^+ \cong 0.4$  (dimensionless wall distance in wall units). For each nominal particle diameter, namely  $d_p = 20, 30, 60$  and  $100\text{ }\mu\text{m}$ , the Lagrangian simulation has been carried out by tracking as much as  $10^6$  particles in order to get enough statistical information in each cell of the domain to calculate the mean velocities and covariances. Due to the lack of available experimental data, the  $160\text{ }\mu\text{m}$  case has not been studied here. Preliminary numerical tests have shown that increasing the number of particles or the number of cells does not modify the results significantly.

The particle-wall collision parameters have been set to the following values : kinetic friction factor  $f = 0.2$ , static friction factor  $f_0 = 0.3$ , coefficient of restitution  $e = 0.95$ . As pointed out by Lain *et al.* [25], the standard deviation of the virtual wall inclination depends not only of the wall structure, but also on the particle diameter. Here, we used the values of  $\sigma_\gamma$  recommended by these authors for low roughness, namely :  $\sigma_\gamma = 0.064$  for  $d_p = 20\text{ }\mu\text{m}$ ,  $\sigma_\gamma = 0.061$  for  $d_p = 30\text{ }\mu\text{m}$ ,  $\sigma_\gamma = 0.052$  for  $d_p = 60\text{ }\mu\text{m}$ , and  $\sigma_\gamma = 0.043$  for  $d_p = 100\text{ }\mu\text{m}$ .

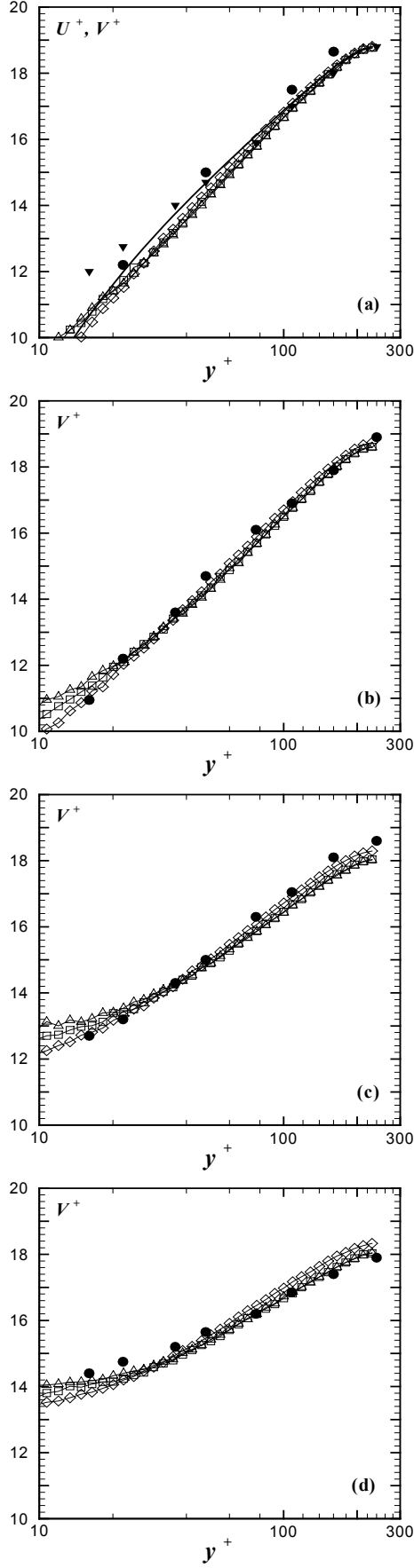
Three models for the Lagrangian time scales  $T_{Li}$  have been tested in each case : the present original model, the anisotropic formulation by Eq. (9) with  $C_L = 0.2$ , and an isotropic model where the time scales in each direction are assumed to be equal to the wall-normal time scale computed by Eq. (14).

## Comparison with experimental results

The dimensionless mean velocities (in wall units) of the fluid,  $U^+$ , and of the particles,  $V^+$ , are plotted in Fig. 1 as a function of the wall distance  $y^+$  for the various particle diameters investigated in [15]. All four plots show relatively good agreement between the measured and predicted velocities. The Eulerian predictions for the mean gas velocity (only shown in Fig. 1(a)) are very satisfactory in the channel core region. Nevertheless, a slight discrepancy for  $U^+$  is noticed very close to the wall, where the Eulerian model seems to underestimate the experimental data. This difference, that never exceeds 10%, seems to be independent from the wall treatment, and can be partly explained by the variations of the measured fluid velocity in the experiments. According to [15], this velocity was found to vary within 2.3% from one case to another in the experiments, however no systematic effect of the particle size was observed. Despite this difference close to the wall, the mean particle velocity  $V_x^+$  is well predicted by the three Lagrangian models, which are seen to differ very slightly in the near wall region. All the numerical results within the whole channel, from wall to centerline, are very close to the experimental data except for the case  $d_p = 60\text{ }\mu\text{m}$  where the experimental results are somewhat underestimated by the simulation in the neighborhood of the channel centerline. The model clearly reproduces the experimental trend of the velocity profile becoming flatter with increasing particle size, a well known behavior which has been observed in many earlier experiments about gas-solid pipe or channel flows. From these comparisons, it may be noticed that the mean particle velocity predictions obtained using any of the three time scale models are very similar, which is not surprising because the choice of the time scale model is expected to mainly influence the particle dispersion and fluctuating velocities.

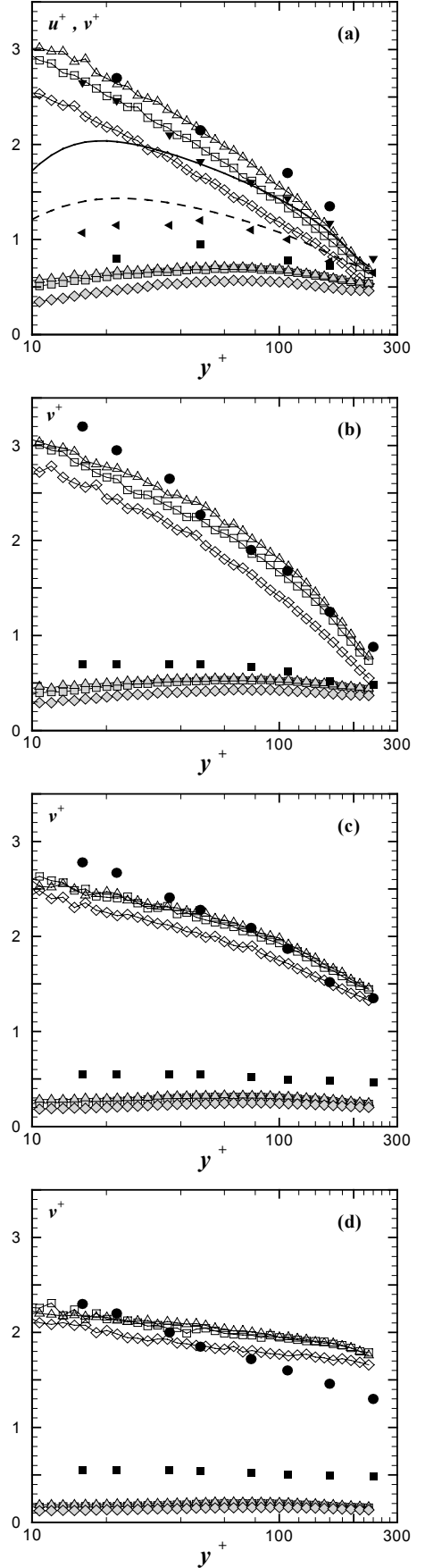
The comparison between the measured and computed profiles of the gas and particle rms velocities ( $u^+$  and  $v^+$ , respectively) is presented in Fig. 2. As shown by Fig. 2(a), the predicted rms velocities of the gas are in good agreement with the experimental ones, except in the near wall region ( $y^+ < 40$ ) where the streamwise fluctuating velocity is somewhat underestimated, showing a local maximum at  $y^+ \cong 20$  which is not visible in the measurements, whereas the spanwise fluctuating velocity is a little bit overpredicted. In spite of this small difference between the measurements [15] and the present predictions of the gas fluctuating velocity

near the wall, the rms velocities of the particles are quite well



**Fig. 1 :** Profiles of dimensionless mean velocities. Experimental data : ▼ unladen gas; ● particles. Numerical results : — unladen gas; particles: -△- present model, -□-

isotropic model, -◇- Eq. (9). (a) Unladen gas and  $d_p = 20 \mu\text{m}$ ; (b)  $d_p = 30 \mu\text{m}$ ; (c)  $d_p = 60 \mu\text{m}$ ; (d)  $d_p = 100 \mu\text{m}$ .



**Fig. 2 :** Profiles of dimensionless rms velocities. Experiments : gas: ▼ streamwise, ▲ spanwise; particles: ● streamwise, ■ spanwise. Numerical results: gas: — streamwise, -- spanwise; particles: same caption as Fig. 1,

with open symbols for the streamwise direction, grey symbols for the spanwise direction. (a),(b),(c),(d) as in Fig. 1. described by the Lagrangian models, as shown by Fig. 2(a)-(d). Except for the case  $d_p = 100 \mu\text{m}$ , where the three models tend to overestimate the streamwise particle rms velocity in the channel centre, the present model can be seen to lead to improved agreement with the measured values. It is interesting to notice that the model with isotropic Lagrangian time scales yields better results than the anisotropic model obeying Eq. (9) and (11). The difference between the three models, which may exceed 20% for the  $20 \mu\text{m}$  particles, decreases with increasing particle diameter. Even if the computed values of the spanwise particle velocity fluctuations from the present model are very satisfactory for the smallest particles, they can be observed to underestimate the experimental results whatever the model used for the Lagrangian time scales, especially for larger particles. It can be concluded from Fig. 2 that the present anisotropic model appears to be more accurate for the prediction of the particle fluctuating velocities.

Additional information about the accuracy of the estimated time scales can be obtained by examining the reduced gas-particle velocity covariances  $\langle u_\alpha v_\alpha \rangle / (u_\alpha v_\alpha)$  ( $\alpha \equiv x, z$ ), whose profiles are displayed in Fig. 3. On the whole, the streamwise and spanwise gas-particle covariances  $\langle u_x v_x \rangle / (u_x v_x)$  and  $\langle u_z v_z \rangle / (u_z v_z)$  computed by means of the proposed model are in acceptable agreement with the experiments. For heavier particles ( $d_p = 60$  and  $100 \mu\text{m}$ ) however, the computed spanwise velocity correlations  $\langle u_z v_z \rangle / (u_z v_z)$  are found to exceed the streamwise ones whatever the model used for the time scales, contrary to the measurements. Nevertheless, the newly proposed model can be seen to significantly enhance the predictions compared to the two other Lagrangian time scale models, especially for the streamwise gas-particle velocity correlation, even though the spanwise velocity correlation in the channel core can be seen to be overestimated by our model and by the isotropic model as well.

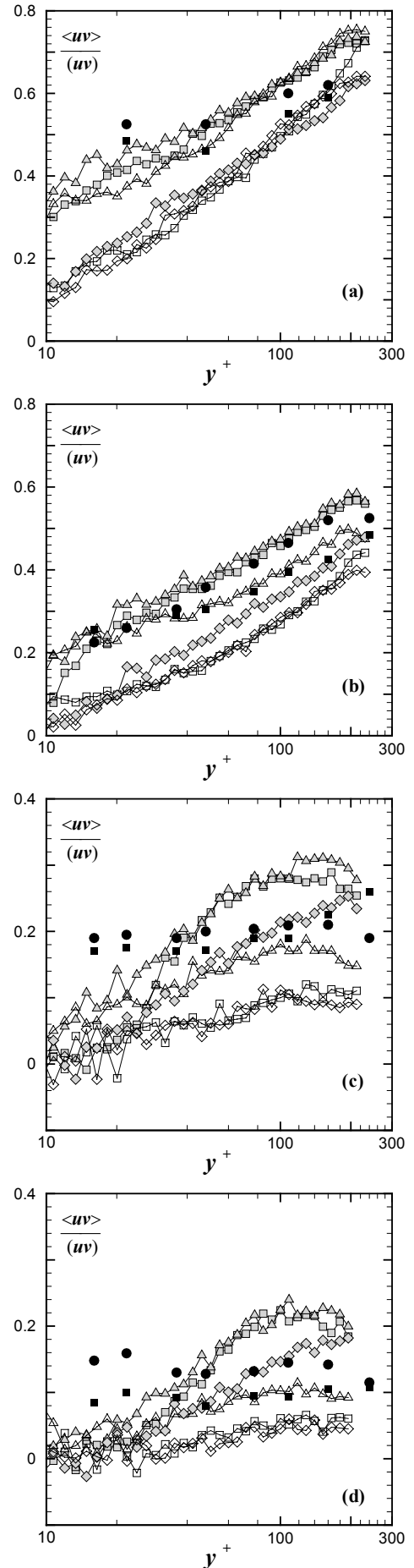
The comparison between the experimental and numerical evaluations of the rms slip velocity in the streamwise and spanwise directions is presented in Fig. 4. Whatever the particle size, the three models yield nearly identical results in very satisfactory agreement with the measurements, even if the rms spanwise relative velocity is slightly overestimated in the near wall region.

From the various comparisons presented for this channel flow test-case, it can be concluded that the prediction of the fluctuating motion of particles suspended in a wall bounded turbulent flow can be improved by the proposed anisotropic dispersion model, especially with regards to the particle fluctuating velocity variances and the fluid-particle velocity covariances.

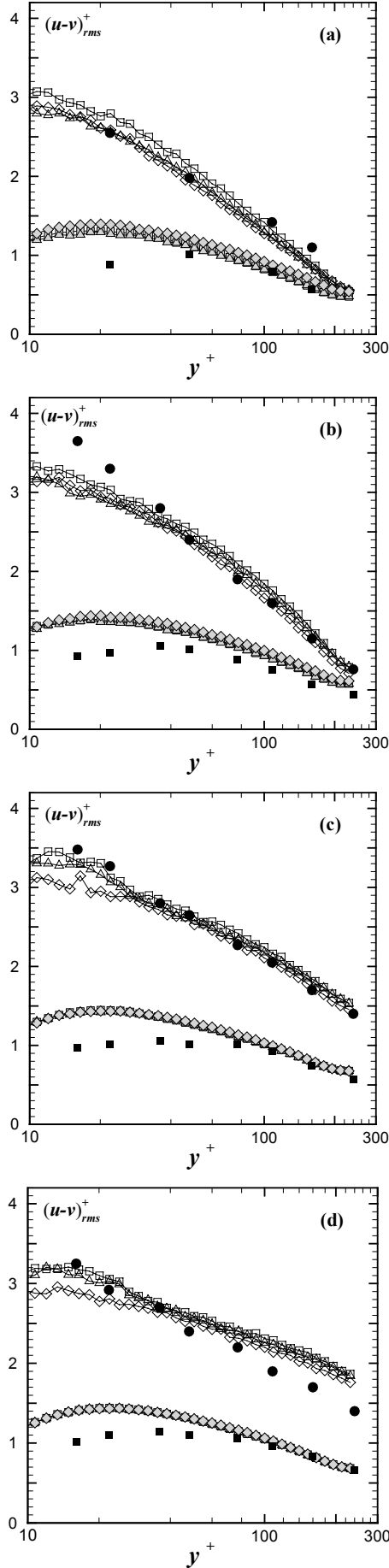
## CONCLUSION

An improved Lagrangian model for the computation of turbulent gas-solid or gas-droplet flows has been presented. By means of accurate modelling of the directional dependence of the fluid Lagrangian time scales, the proposed dispersion model is able to take into account the non homogeneous and anisotropic character of the turbulence. Through comparison with recent experimental data obtained in a channel flow by Khalitov and Longmire [15], the method

has been shown to be a performing tool for the simulation of the dispersed phase motion in a gas-solid turbulent flow. Evaluation of the second order statistical moments of the fluid and particle velocities



**Fig. 3 :** Profiles of dimensionless gas-particle covariances.  
Same caption as in Fig. 2. (a),(b),(c),(d) as in Fig. 1.



**Fig. 4 :** Profiles of dimensionless rms slip velocities.

Same caption as in Fig. 2. (a),(b),(c),(d) as in Fig. 1. appears to be significantly improved when compared to the predictions obtained by means of previous models for the fluid Lagrangian time scales.

However, some discrepancies between the predictions and the measured data remain, showing that there is still scope for improvement in such anisotropic dispersion models. Further investigations are needed to obtain new numerical data about the the integral time scales of the fluid flow, including the moving Eulerian time scales, and about the relationships with the time scales of the fluid seen by discrete particles in terms of their Stokes number and mean slip velocity.

## NOMENCLATURE

$d_p$	particle diameter (m)
$e$	coefficient of restitution (dimensionless)
$f$	kinetic friction factor (dimensionless)
$f_0$	static friction factor (dimensionless)
$h$	channel half-width (m)
$k$	turbulent kinetic energy ( $\text{m}^2\text{s}^{-2}$ )
$L_f$	longitudinal integral length scale (m)
$Re_h$	channel flow Reynolds number (dimensionless)
$St$	particle Stokes number (dimensionless)
$T_i^*$	integral time scales of the fluid seen by the particles (s)
$T_{Li}$	fluid Lagrangian time scales (s)
$T_{mEi}$	moving Eulerian time scales (s)
$t$	time (s)
$U_i$	instantaneous velocity of the fluid ( $\text{ms}^{-1}$ )
$u_i$	fluid velocity fluctuation ( $\text{ms}^{-1}$ )
$u_i^*$	fluid velocity fluctuation seen by a discrete particle ( $\text{ms}^{-1}$ )
$U^+$	dimensionless mean velocity of the fluid, in wall units
$u^+$	dimensionless rms velocity of the fluid, in wall units
$V^+$	dimensionless mean velocity of the particles, in wall units
$V_r$	mean relative velocity ( $\text{ms}^{-1}$ )
$v_i$	particle velocity fluctuation ( $\text{ms}^{-1}$ )
$v^+$	dimensionless rms velocity of the particles, in wall units
$x, y, z$	streamwise, wall-normal and spanwise coordinates (m)
$y^+$	dimensionless wall distance, in wall units

## Greek letters

$\varepsilon$	turbulent kinetic energy dissipation rate ( $\text{m}^2\text{s}^{-3}$ )
$\psi, \varphi, \chi$	centered Gaussian variables
$\nu_t$	eddy viscosity ( $\text{m}^2\text{s}^{-1}$ )
$\sigma_\gamma$	standard deviation of the virtual wall inclination (rad)
$\tau_p$	particle relaxation time (s)

## Subscripts

$i, j$ or $x, y, z$	direction of vector components
$n$	time level



## Others

$\langle \cdot \rangle$  averaged quantity

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