VALIDATION OF SECOND-ORDER MOMENT TURBULENCE MODELS USING LARGE EDDY SIMULATION AND EXPERIMENTS FOR TURBULENT TWO-PHASE FLOWS

Bernd Groh*, Mouldi Chrigui, Zdravko Stojanovic, Amsini Sadiki, Andreas Dreizler, Johannes Janicka

Chair of Energy and Powerplant Technology, Department of Mechanical Engineering,
Darmstadt University of Technology
Petersenstr. 30, 64287 Darmstadt, Germany
*bgroh@ekt.tu-darmstadt.de

ABSTRACT

Both, numerical results obtained with Large Eddy Simulation (LES) and experimental data are used to validate Reynolds-Averaged Navier-Stokes (RANS) calculations. These are performed to study the phenomenon of augmentation and attenuation of fluid turbulence due to the presence of dispersed particles, known as turbulence modulation. An Eulerian/ Lagrangian treatment is used, in which the dispersed properties are obtained from tracking discrete particles in a dilute two-phase flow.

In particular the effect of varied diameters and different volumetric loading ratios are investigated. The modulation model presented in Chrigui et al. (2003) captures well the attenuation and the augmentation of the induced turbulence. Small particles of 120 μm diameter attenuate the fluid turbulence, while particles of 480 μm diameter generate fluid turbulence. Varied volumetric loading ratios for particles of 120 μm diameter show, that a lower volumetric loading ratio tend to attenuate the fluid turbulence towards a flow without tracked particles. This trend is confirmed with energy power-spectra from experiments and LES.

INTRODUCTION

Since more than ten years numerical simulation continues to evolve as an important tool in the analysis and prediction of dispersed two-phase flows, in particular for studying the fundamental interactions governing a flow. These flows are as diverse as pollutant dispersion in the atmosphere, contaminant transport in industrial applications, coal injection into entrained flow gasifiers or conveying of powder in transport lines. At this practical level of engineering applications, numerical simulations mostly rely on solution of a RANS equation set. Many of the statistical correlations requiring closures in statistically-averaged equations are often difficult or impossible to measure in experimental investigations of two-phase flows, limiting our understanding of many aspects, such as particle dispersion or turbulence modulation by particles.

Despite the difficulties associated with various methods of study, there is considerable progress in this field. Kulick et al. (1994) conducted experiments in a channel flow and found that turbulence attenuation increases with both mass loading and particle Stokes number. Several other experimental studies in shear flows and boundary layers have shown that turbulent velocity fluctuations may be either increased or decreased due to the modulation of the flow by heavy particles (e.g see Rogers and Eaton (1991)).

In the recent time numerical studies have become an important tool to examine the modulation of turbulence by particles. The most sophisticated numerical approach for examining particle-turbulence interactions is Direct Numerical Simulation (DNS). In DNS the Navier-Stokes equations are solved without resorting to ad hoc modeling at any scale of motion. The primary advantage for calculations of particle-laden flows is that turbulence properties along particle trajectories are directly available. Elghobashi and Truesdell (1993) examined turbulence modulation in decaying isotropic turbulence and found that the coupling between particles and fluid resulted in an increase in small-scale energy. They also found that the effect of gravity resulted in an anisotropic modulation of the turbulence and an enhancement of turbulence energy levels in the direction aligned with gravity. For recent work, see Mashayek (2001).

Where DNS cannot be performed, Large Eddy Simulation, which directly resolves the large turbulent eddies, and only models the influence of the small subgrid scales of motion on the large eddies, is an important component besides experiments in evaluating closure models. In the literature only a few studies concerning the influence of particles towards the modulation of fluid turbulence are reported. Boivin et al. (2000) examined the feasibility of LES for predicting gas-solid flows in which the carrier flow turbulence is modified by momentum exchange with particles. They concluded that good agreement and independency of mesh refinement is obtained when using closures for subgrid-scale turbulence models whose coefficients are computed dynamically. One major drawback of the findings of Boivin et al. (2000) was the neglect of subgrid-scale fluid velocity fluctuations on particle transport. Kangbin et al. (2001) proposed therefore a new subgrid model and examined their influence onto fluid turbulence. With regard to the validation of RANS-models for particle-laden flows within an Eulerian/ Eulerian framework, Wang et al. (1997) used LES for predicting gas-solid flows without any comparison with experimental data.

The present study applies an Eulerian/ Lagrangian approach, that accounts for full two-way coupling to a well experimentally investigated turbulent two-phase flow. The effects of turbulence modulation phenomena, i.e. the augmentation and the attenuation of the turbulence due to the presence of particles is analyzed and discussed. In particular the effects of varied diameters and different volumetric loading ratios are pointed out. RANS calculations are validated by comparing the obtained results with LES and experimental measurements.

CONFIGURATION OF THE FLOW

Comprehensive experiments were performed at the Institut of Energy- and Powerplant at the Technical University of Darmstadt in a special designed vertical closed-circuit wind-tunnel. The considered flow is a grid-generated isotropic homogeneous turbulent flow. The hole-diameter M of the grid is 0.012 m and the bulk velocity is up to 12 m/s, corresponding to a Reynolds-number of 64000, relying on the channel half-width. The test-section is designed as a vertical square tunnel with inner dimensions of 0.2 m by 0.2 m. Air is used as the continuous phase and solid non-reacting particles with various diameters and different volumetric loading ratios act as the dispersed phase. All properties of the dispersed phase are listed in Table 1. A full data set for this configuration is available from experiments using 2-D phase-Doppler anemometry (PDA) to obtain velocities and higher moments for both phases. Particle concentration measurements are performed by conventional probe (patternator) techniques. All data and a detailed description of the experimental setup can be found in Geiss et al. (2001).

Case	D_d [m]	ρ_d $[m^3/kg]$	ϕ_d [-]
A	-	-	0.0
B	1.22×10^{-4}	2440	2.3×10^{-5}
C	1.22×10^{-4}	2440	4.5×10^{-5}
D	1.22×10^{-4}	2440	8.5×10^{-5}
E	4.80×10^{-4}	2440	4.1×10^{-4}

Table 1: Particle properties of the considered flow configurations

MODELING AND NUMERICAL APPROACH

Gas phase treatment

For LES the gas phase flow field is described by the filtered equation of continuity together with the three-dimensional filtered[1] Navier-Stokes equations for variable density fluids,

$$\frac{\partial \bar{\rho}^{\Delta}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{\rho}^{\Delta}\tilde{u}_j^{\Delta}\right) = 0 \qquad (1)$$

$$\begin{aligned}\frac{\partial}{\partial t}\left(\bar{\rho}^{\Delta}\tilde{u}_i^{\Delta}\right) &= -\frac{\partial}{\partial x_j}\left(\bar{\rho}^{\Delta}\tilde{u}_i^{\Delta}\tilde{u}_j^{\Delta}\right) - \frac{\partial \bar{p}^{\Delta}}{\partial x_i} + \bar{\rho}^{\Delta} g_i \\ &+ \frac{\partial}{\partial x_j}\left[\bar{\mu}^{\Delta}\left(\frac{\partial \tilde{u}_j^{\Delta}}{\partial x_i} + \frac{\partial \tilde{u}_i^{\Delta}}{\partial x_j}\right)\right. \\ &\left. - \frac{2}{3}\bar{\mu}^{\Delta}\frac{\partial \tilde{u}_k^{\Delta}}{\partial x_k}\delta_{ij} + \bar{\rho}^{\Delta}\tau_{ij}^{sgs}\right] \\ &+ F_{s,i} \qquad (2)\end{aligned}$$

where $\bar{\rho}^{\Delta}, \tilde{u}_i^{\Delta}, \bar{p}^{\Delta}, \bar{\mu}^{\Delta}, g_i, F_{s,i}$ are filtered density, velocity components, pressure and dynamic viscosity, the gravity components and the volume-averaged interphase source term respectively. Sub-grid scale stresses τ_{ij}^{sgs} are closed using Germano's (1991) dynamic procedure. Because the Mach-number of the flow is low, density is assumed to be independent of pressure (incompressibility).

Equations (1), (2) were discretised in space by finite volumes utilizing central schemes. The accuracy of approximation is 4th order for convective terms and 2nd order for all other terms. The equations of the Eulerian gas field and the Lagrangian dispersed phase are integrated in time by a 3rd order low-storage Runge-Kutta method, pressure is determined by solving a Poisson equation derived from the equation of continuity.

While Kangbin et al. (2001) used $64 \times 32 \times 32$ cells for particle-laden channel flow and Laviéville et al. (1995) used (64^3) cells for a homogeneous isotropic turbulence, for the LES computation, a computational grid of $128 \times 32 \times 32$ cells is used in this work.

To generate the measured turbulence level of first and second order statistics in the experiments, inflow boundary conditions for LES calculations are reproduced with the inflow-generator. A detailed descrip-

[1]the notation $()^{\Delta}$ indicates a filtered quantity throughout the text

tion of the proposed procedure to generate more physical turbulence data for numerical simulation, which is a well known problem in the DNS and LES-community can be found in Klein et al. (2002).

For solving the RANS equation set, that can be explicitely found in Chrigui et al. (2003), the finite volume method is used on a nonorthogonal block structured grid. SIMPLE-alghorithm is used for velocity-pressure coupling and time integration is done implictly with the method of Crank-Nicholson. The gas flow field is predicted on a computational grid of $58 \times 38 \times 38$ cells.

Transport of Particles

An Eulerian/ Lagrangian apporach is employed here, in which the particles are tracked in a Lagrangian sense within an Eulerian gas field. In this method particles groups (that represent particles of same size, location and velocities) are tracked instead of each single particle.

Under the assumption that the density of the dispersed phase is much larger than the fluid density, the Basset-Boussinesq-Oseen (BBO) equation of particle motion includes drag and the influence of gravity. The modeled Lagrangian equations for the transient position and velocity of a particle group d are

$$\frac{dX_i}{dt} = v_i \tag{3}$$

$$\frac{dv_i}{dt} = \frac{F_i}{m_d}; \quad \text{with} \tag{4a}$$

$$F_i = m_d\left(\frac{1}{\tau_d}\right)(u_i - v_i) + m_d g_i \tag{4b}$$

where X_i represents the particle position, m_d the mass, v_i the particle velocity components and u_i the instantaneous fluid velocity components at the particle position. The particle-relaxation time τ_d is

$$\tau_d = \frac{4D_d\rho_d}{3C_d\bar{\rho}^{\Delta}|u_i - v_i|} \tag{5}$$

with D_d as the particle diameter and ρ_d as the density of a particle group. The particle-drag coefficient C_d follows as

$$C_d = \frac{24}{Re_d}(1 + 0.15Re_d^{0.687}) \tag{6}$$

with the particle Reynolds-number,

$$Re_d = \frac{|u_i - v_i|D_d}{\tilde{\nu}^{\Delta}} \tag{7}$$

where $\tilde{\nu}^{\Delta}$ is the filtered kinematic viscosity of the fluid.

The number of numerical particles in the case of RANS were 20000. Laviéville et al. (1995) used 30000-625000 numerical particles for a homogeneous isotropic turbulence, we use for the LES computation 300000 numerical particles. Each numerical particle represent up to 50 real particles in the experiment.

Dispersion of Particles

Stochastic motion of the particles due to turbulent motion is included for LES by representing the instantaneous gas phase velocity at the particle position as the sum of the local gas phase and subgrid-root-mean-square velocity $u_i = \tilde{u}_i^{\Delta} + u_i^{sgs}$, with

$$u_i^{sgs} = L_G\sqrt{2k^{sgs}/3} \tag{8}$$

and the turbulent kinetic subgrid energy k^{sgs} derived from the estimation of Lilly (1967),

$$k^{sgs} = \frac{\tilde{\nu_t}^2}{(0.094\Delta)^2} \tag{9}$$

where $\tilde{\nu_t}$ is the turbulent kinematic viscosity, Δ is the filter width of the fluid and L_G is a random number sampled from a Gaussian distribution (with zero mean).

Stochastic dispersion of the particles in the frame of RANS is achieved by using the semi-empirical Markov-sequence model. A detailed description of the modeling of the dispersion can be found in Kohnen et al. (1998).

Two-way coupling and Turbulence modulation

In the transport equations in RANS and LES appropriate particle source terms are accounted for, so that a two-way coupling is achieved along with the turbulence modulation modeling. Only in RANS a turbulence modulation model is included, which accounts not only for the attenuation but also for the augmentation of the induced turbulence. The model is derived from a thermodynamically consistent concept, in which the energy balance is included. Therefore it contains the so called consistent term by Crowe (2000) and an additional exchange term, expressing the transfer of kinetic energy between phases. This last term is mainly negative. For details, the reader is refered to Chrigui et al. (2003).

The volume averaged inter-phase source term $F_{s,i}$, that appears on the right hand side of the LES momentum equation is given by (compare to equation (4b)),

$$F_{s,i} = -\sum_d \left[\frac{w_d m_d N_d}{V_{i,j,k}}\left(\frac{1}{\tau_d}\right)(u_i - v_i)\right] \tag{10}$$

where w_d is a volume-weighted averaging factor, N_d the number of real particles reresented by one numerical particle and $V_{i,j,k}$ the volume of a discretised computational grid cell, respectively. A simple eight-point, volume-weighted averaging of the adjacent cells is used to interpolate the gas phase properties to the particle locations and for redistribution of the particle source terms form the particle position to the Eulerian grid.

For LES the momentum transfer between the continuum and the dispersed phase is included at every single Runge-Kutta time step, while for the RANS model the momentum exchange between the continuum and the dispersed phase is included at each pass-through time. The different treatment for particle source terms in LES and RANS is explained by the unsteady character of the

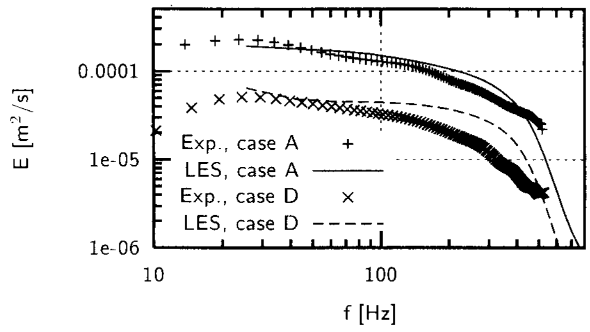

Figure 1: Comparison of longitudinal velocity energy density for single phase flow (case A) and flow with particles (case D)

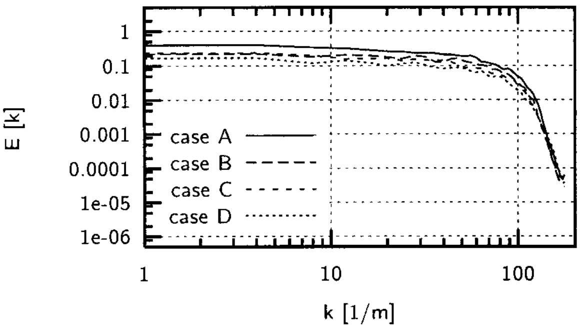

Figure 2: Comparison of LES calculated spatial energy spectrum for single phase flow and two-phase flow with particles for case A - D

LES simulation with a strong numerical coupling between the fluid and the dispersed phase in the FLOWSI-3D code, compared to the steady RANS simulation with almost two stand-alone code-parts (FASTEST-3D CFD code and Lagrangian LAG-3D code) to evaluate the gas- and the particle-phase.

DISCUSSION OF RESULTS

Before we go into detail of the validation of RANS calculations, we first compare LES results with experimental data.

Comparison of LES and experiments

The results agree very well in the prediction of the dynamics of particles and of the influence of small particles on the the fluid. Figure 1 shows a comparison of temporal energy spectra from experiments and calculated LES spectra for a flow without particles (case A) and a flow with particles (case D). The content of energy of the carrier-phase (air) is attenuated by the presence of the particle phase. In order to examine whether the reduction of the turbulent kinetic energy is uniformly or preferential distributed over the scales of turbulence, we display in Figure 2 LES calculated spatial energy spectrum for case A (single phase flow) and for case B - D (a flow with laden particles). As mentioned by Elghobashi and Truesdell (1993), who examined the influence of particles in a decaying homogeneous turbulence by means of DNS, one can see the redistribution of turbulence energy due to the presence of particles is not uniform. As expected for small particles with a diameter $D_d < \eta = 0.11mm$ (η as Kolmogorov length scale), particles transfer their momentum to the high wave number motion of the carrier fluid. The energy content of small scales is increased in relation to a flow without particles (case A). Regarding the region of low wave number motion, the presence of particles under the influence of gravity attenuate the fluid turbulence level.

To well capture the effect of particles, the consideration requires appropriate modulation models, that are capable of predicting not only the attenuation of the induced turbulence but also the augmentation in an efficient manner. If this is the case for LES, one can then state, that LES calculations can be used to validate RANS calculations where experiments are not available. For the considered range of particles sizes and concentrations, we use at this stage both LES and experimental data to validate results obtained from RANS simulations using the second-order turbulence model of Launder-Reece-Rodi (1975) completed with particle source terms. Because measured data was available only for statistical moments (means, variances) and correlations, the discussion is restricted to these quantities.

When comparing the results obtained with LES to those obtained with RANS calculations, we consider LES samples to be statistically independent. To get qualitative good moments of first and second order, samples were gathered every 200 timesteps and each grid point of the homogeneous direction.

Validation of RANS calculations without particles

To validate second-order moment turbulence models by LES simulations and measurements, it is first shown in Figure 3 for case A, that LES results agree nicely with the measured data for the considered channel flow, in which the dispersed phase is not allowed to influence the fluid motion [$F_{s,i} = 0$ in Eq. (10)]. Results for the RANS simulation predict the measured decay of the turbulent kinetic energy with good accuracy.

Validation of RANS calculations with particles

Before evaluating the capability of RANS models to predict the fluid turbulence modulation, Figures 4 and 5 show results for LES simulations compared to measurements for the mean axial velocity and for the turbulent kinetic energy of the dispersed phase exemplary for case D (results for this diameter but with different volumetric loading ratios show almost equal results) and for case E. Regarding the dispersed phase, LES results describe the measured data very well. This indicates, that the considered dispersion model for RANS simulations is acceptable.

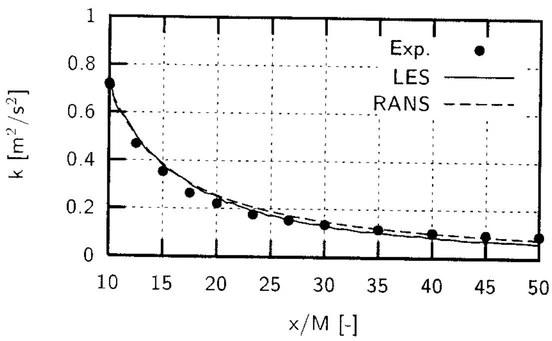

Figure 3: Centerline decay of turbulent kinetic energy of the gas-phase (air) for case A

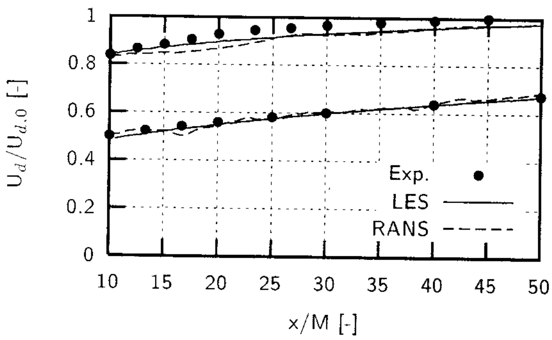

Figure 4: Centerline distribution of the mean axial velocity of the dispersed-phase for case D (upper curve) and E (lower curve)

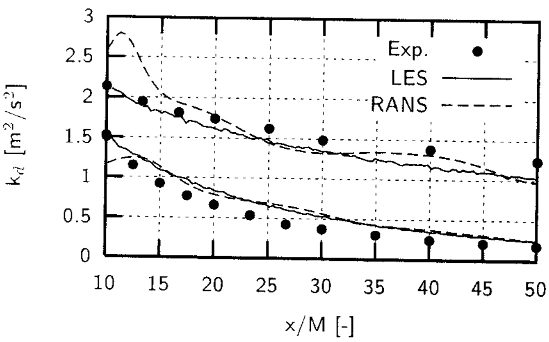

Figure 5: Centerline decay of turbulent kinetic energy of the dispersed-phase for case D (lower curve) and E (upper curve)

In Figure 6 - 8 results for RANS simulations are compared to LES results and measurements for the turbulent kinetic energy of the carrier-phase (air) for case B - D. A good agreement is obtained. The predictions of RANS results for the carrier-phase (air) for $x/M > 20$ tend to predict more attenuation of the turbulent kinetic energy than measurements show. This trend is independent of the particle volumetric loading ratio and also confirmed by results of the LES simulations.

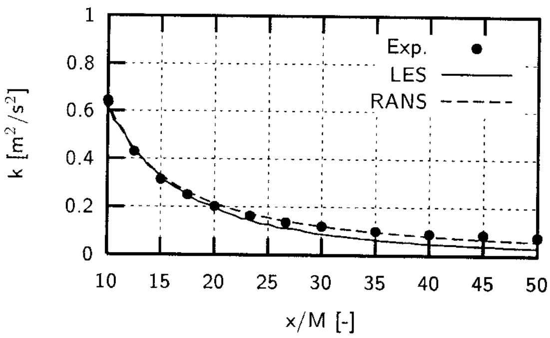

Figure 6: Centerline decay of turbulent kinetic energy of the carrier-phase (air) for case B

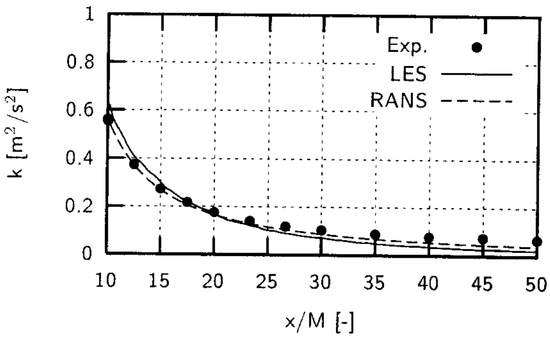

Figure 7: Centerline decay of turbulent kinetic energy of the carrier-phase (air) for case C

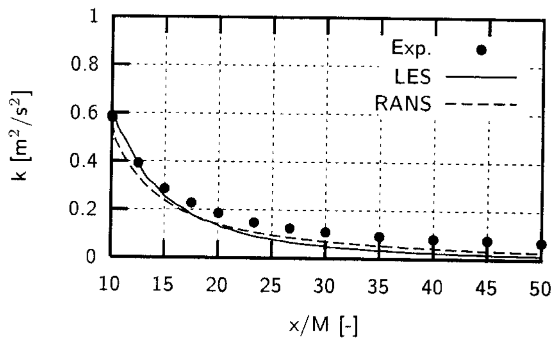

Figure 8: Centerline decay of turbulent kinetic energy of the carrier-phase (air) for case D

The influence of the particle size is distinguished in Figure 9, in which results for RANS simulations are compared to LES results and measurements for the turbulent kinetic energy of the carrier-phase (air) for case E. Large particles of this size generate fluid turbulence, which is not predicted by LES calculation due to

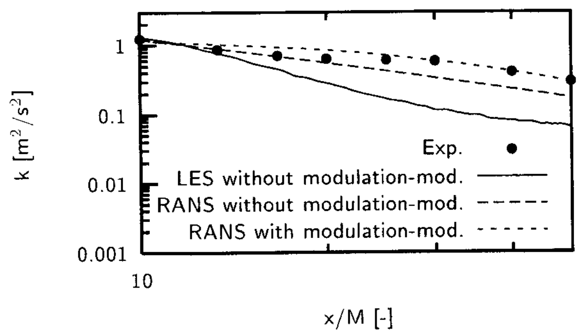

Figure 9: Centerline decay of turbulent kinetic energy of the carrier-phase (air) for case E in logarithmic plotting

the lack of coressponding contribution in the modeling. From Figure 9 one can observ that the term $F_{s,i}$ in Eq. (2) acts as a source (sink) in the transport equation in the physical space. Results for the turbulence modulation model in the RANS equation set agree well with measurements.

SUMMARY AND CONCLUSIONS

In the present study we numerically and experimentally analyze the performance of an Eulerian/ Lagrangian approach in predicting the modulation of fluid turbulence. Results show clearly the applicability of RANS-models coupled to the modulation model presented in Chrigui et al. (2003) in combination with the Markov-Sequence dispersion model. This coupling accounts well for the augmentation and attenuation of the induced turbulence due to the particle phase. Results of the energy spectrum demonstrate that small particles transfer their momentum to the high wave number motion, for which the energy content of small scales is increased.

In order to make LES an efficient tool to validate RANS-models, more studies have to be accomplished and appropriate modulation models have to be developed, capable of predicting simultaneously the augmentation and the attenuation of processes in polydispersed two-phase flows.

ACKNOWLEDGEMENT

For financial support we gratefully acknowledge the Deutsche Forschungsgemeinschaft contract number Ja 544/27-1, Ja 544/21-2 and the Sonderforschungsbereich 568 (Project A4).

REFERENCES

Boivin, M., Simonin, O. and Squires, K. D., 2000, "On the prediction of gas-solid flows with two-way coupling using large eddy simulation", *Phys. of Fluids*, Vol. 12, pp. 2080-2090

Chrigui, M., Ahmadi, G. and Sadiki, A., 2003, "Study of interaction in spray between evaporating droplets and turbulence using second-order turbulence models and a lagrangian approach", *Progress in Computational Fluid Dynamics*, in press

Crowe, C. T., 2000, "On models for turbulence modulation in fluid-particle flows", *Int. J. Multiphase Flow*, Vol. 26, pp. 719–727

Elghobashi, S. and Truesdell, G. C., 1993, "On the twoway interaction between homogenous turbulence and dispersed solid particles I: Turbulence modification", *Phys. of Fluids A*, Vol. 5, pp. 1790–1801

Geiss, S., Stojanovic, Z., Sadiki, A., Maltsev, A., Dreizler, A. and Janicka, J., 2001, "Measurements and Numerical Prediction of Flow and Particle Fields in Turbulent Particle-Laden Flows-Turbulence Modulation", *Proceedings, 2nd TSFP*, Vol. 2, pp. 347–352

Germano, M., Piomelli, U., Moin, P., and Cabot, W. H., 1991, "A dynamic subgrid-scale eddy viscosity model," *Physics of Fluids A*, Vol. 3, pp. 1760–1765

Kangbin, L., Taniguchi, N. and Kobayashi, T., 2001, "A New Dynamic SGS-Model for Large Eddy Simulation of Particle-Laden Flows", *Proceedings, 3rd AFOSR Int. Conference on DNS/ LES*

Klein, M., Sadiki, A. and Janicka, J., 2002, "A digital filter based generation of inflow data for spatially developing direct numerical or large eddy simulation", *J. Comp. Physics*, in press

Kohnen, G. and Sommerfeld M., 1997, "The Effect of turbulence modeling on turbulence modification in two-phase flows using the Euler-Lagrange approach", *11th TSF*, Grenoble, Vol. 3, pp. 23–28

Kulick, J. D., Fessler, J. R. and Eaton, J. K., 1994, "Particle response and turbulence modification in fully developed channel flow", *J. Fluid Mech.*, Vol. 277, pp. 109–134

Launder, B. E., Reece, G. C. and Rodi, W., 1975, "Progress in the development of a Reynolds-stress turbulence closure", *J. Fluid Mech.*, Vol. 68, pp. 537–566

Laviéville, J., Deutsch, E. and Simonin, O., 1995, "Large Eddy Simulation of interactions between colliding particles and a homogeneous isotropic turbulence field", *Gas Solid Flows, ASME FED*, Vol. 228, p. 347

Lilly, D. K., 1967, "The representation of small-scale turbulence in numerical simulation experiments", *Proceedings of the IBM Scientific Computing Symp. on Enviromental Sciences*, 320-1951, pp. 195–210

Barré, C., Mashayek, F. and Taulbee, D. B., 2001, "Statistics in particle-laden plain strain turbulence by direct numerical simulation", *Int. J. Multiphase Flow*, Vol. 27, pp. 347–378

Rogers, C. B. and Eaton, J. K., 1991, "The effect of small particles on fluid turbulence in a flate plate turbulent boundary layer in air", *Physics of Fluids*, Vol. A 3, pp. 928

Wang, Q., Squires, K., D. and Simonin, O., 1997, "Large Eddy Simulation of turbulent gas-solid flows in a vertical channel and evaluation of second-order models", *11th Symp. on Turbulent Shear Flows*, Grenoble