Turbulence modulation by particles in Large Eddy Simulation of backward-facing step flow

Jaroslav Volavy\textsuperscript{1}, Matej Forman\textsuperscript{1}, Miroslav Jicha\textsuperscript{1}
\textsuperscript{1}Faculty of Mechanical Engineering, Brno University of Technology, Technick 2896/2, 616 69 Brno, Czech Republic
E-mail: jaroslav.volavy@gmail.com

Abstract. Large Eddy Simulation of backward-facing step flow laden with particles were performed. The number of particles is chosen very large and the volume fraction of particles is high enough for consideration of two-way coupling. This means that the particles are influenced by fluid and vice versa. The inter-particle collisions are neglected. The Euler-Lagrange method is adopted, which means that the fluid is considered to be continuum (Euler approach) and for each individual particle is solved Lagrangian equation of motion. Particles are considered to be spherical. The simulations are performed for different mass fractions of 90 \text{\mu m} glass particles. The results are compared to the single-phase flow in order to investigate the effect of the particles on the turbulence statistics of the carrier phase.

1. Introduction

One of the most interesting problem of fluid dynamics is the solution of turbulent flow with the presence of disperse phase in the mainstream. This type of flow can be found in many industrial applications, eg in the chemical industry, coal-fired power plants in the transportation of coal dust to the boiler, in the prediction of air pollution and many others. It is very important to resolve the flow and turbulence of the carrier phase in order to determine movement of disperse phase (particles) with sufficient precision because this affects transportation and deposition of particles most. In cases where the concentration of particles in the flow is not high (volume fraction of dispersed and carrier phase \( \alpha_p < 10^{-6} \)), we can consider only the so-called one-way coupling Sommerfeld, Wachen & Oliemans (2007). This means that the fluid affects the particles and it is not affected by the presence of the particles ("stream does not know about particles"). Whenever the volume fraction exceeds the value of \( \alpha_p > 10^{-6} \), then the presence of the particles could not be neglected and it is necessary to use two-way coupling (fluid flow affects the particles and vice versa). In this case the turbulence is modulated by particles.

There were done many studies investigating the effect of the particles on the turbulence of the carrier phase in the past. The overview of these works is given by Gore & Crowe (1991). They have done summary of experimental data concerning systems fluid/solid phase in channels and jets. They identified the ratio of particle diameter and turbulence length scale to be suitable parameter for decision whether the turbulence will be enhanced or attenuated. Another study was done by Kulick & Fessler & Eaton (1994). The aim of their stud was to estimate the quantitative changes of the turbulence intensity with particles in the stream. They determined
that the attenuation of the turbulence rise with raising Stokes number of the particles. They also showed, that the turbulence is more attenuated in the region with high spatial frequencies.

The numerical studies of the particle-laden flows were also done. Squires & Eaton (1990) performed DNS simulation of forced homogeneous turbulent flow with particles. They have discovered that the additional source term from particles in the equation of motion acts as a dump for turbulent kinetic energy. The turbulence dissipation increased because of presence of small particles. The simulation of free decaying was done by Elghobashi & Truesdell (1993). They concluded, that the turbulence decay faster with the particles than without them.

In this work is done Large Eddy Simulation of particle-laden backward facing step flow. The simulations were done for three different mass fraction of 90 µm glass particles. The results are compared to the single-phase flow in order to investigate the effect of the particles on the turbulence statistics of the carrier phase.

2. Governing equations

The system of carrier phase (liquid) and dispersed phase (particles) is described in this work using Euler-Lagrange approach. This means that the liquid is considered to be continuum and its motion is described by the Euler equation of motion. The particles are considered as mass points and for their simulation is used Lagrangian approach. For each particle is assembled equations of motions based on the second Newton’s law.

2.1. Liquid phase

For the solution of the fluid flow in this article was chosen Large Eddy Simulation. The main idea of Large Eddy Simulation is to separate large scales (grid-scales) from small scales (subgrid-scales) to lower computational cost. The subgrid scales are modelled using subgrid model. The scale separation is done by applying filter operator on Navier-Stokes equation. If we apply the filter operator on Navier-Stokes equations we obtain filtered Navier-Stokes equations:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i \bar{u}_j) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} - \frac{\partial \tau_{ij}}{\partial x_j} + f_i,$$ (1)

where $f_i$ is coupling force which takes into account the presence of the particles. This force is defined as:

$$f_i = \sum_{n=1}^{N} f_{n,i}$$ (2)

$f_{n,i}$ is the $i$-th component of force acting on the $n$-th particle. Force $f_{n,i}$ is equal to the rand hand side of 5.

For evaluation of subgrid stress tensor $\tau_{ij}$ is used Smagorinsky model:

$$\tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} = -2\nu_t S_{ij}, \quad \nu_t = (C_S \Delta)^2 |\bar{S}|$$ (3)

$$S_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$ (4)

where $|\bar{S}| = |2S_{ij}S_{ij}|^{1/2}$. 

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2.2. Solid phase
The motion of particles is described by Lagrangian equations of motion for each particle. The only force considered here is drag force. Because of high concentration of particles we consider the influence of particles on the fluid. The equation of motion for particle is:

\[ \frac{dv_j}{dt} = u(x_j, t) - v_j \left( 1 + 0.15R_e^{0.687} \right), \]  

where \( v_j \) is velocity of \( j \)-th particle, \( u(x_j, t) \) is velocity of fluid on particle position \( x_j \), \( \tau_p = \rho_p d_p^2 / (18 \rho f \nu) \) is particle relaxation time. The standard drag correlation is applied.

3. Description of the test case
For testing of different approaches to the inlet boundary condition was chosen backward-facing step flow. This case of flow is good benchmark for validating various models because it contains massive separation and consequent re-attachment. Separation bubble on the wall opposite to the step could appear for some geometrical and flow parameters.

The geometry and flow properties was chosen according to the experimental study done by Fessler & Eaton (1999). The Reynolds number of the inlet channel flow was 13 800, based on the bulk velocity of 10 m/s and the channel half-width of 20 mm. The expansion ratio was 5/3. The flow parameters of the inlet channel and backward facing step flow are in table 1.

| Table 1. Flow parameters |
|--------------------------|
| Channel flow | Backward-facing step flow |
| Channel half-width, \( h \) | 20 mm | Step height, \( H \) | 26.7 mm |
| Centerline velocity, \( U_0 \) | 10.5 m/s | Expansion ratio | 5:3 |
| \( Re_h = \frac{U_0 h}{\nu} \) | 13 800 | \( Re_H = \frac{U_0 H}{\nu} \) | 18 400 |
| \( u_r \), friction velocity | 0.5 m/s | \( \tau_f \), large eddy time scale, \( 12.7 \text{ ms} \) |
| Viscous length scale | 31 \( \mu \text{m} \) |
| Kolmogorov length scale, \( \eta \) | 170 \( \mu \text{m} \) |

Figure 1. The detail of the mesh near the trailing edge.
The computational mesh consists of 2.1 million hexahedral cells. The mesh is block-structured and becomes finer towards the wall in order to satisfy condition of $y^+ \approx 1$. The detail of the mesh near the trailing edge is in the Figure 1.

For the generation of the velocity on the inlet to the domain was used direct mapping approach Kaltenbach et al. (1999). The velocity on the inlet is obtained by direct mapping of the velocity from the plane with $3h$ (60 mm) offset from the inlet plane. The schematic picture of the mapping is shown in the Figure 2 (the placement of the mapping plane in this figure is only schematic). For the flow initialization was used following procedure: First was done simulation of inlet channel only using periodic boundary condition. For faster transition to the fully developed turbulent flow was used forcing scheme based on Ornstein-Uhlenbeck process proposed by Volavy & Forman & Jicha (2010). When the fully turbulent regime was reached then the results of this pre-simulation was mapped to the inlet channel of the backward-facing step geometry.

![Figure 2. Scheme of inlet data mapping.](image)

4. Results

In this section are described results of the simulations. Results of the unladen flow are introduced first, than follow results for particle laden flows with different mass fractions particles. The simulations were performed in open-source CFD code OpenFOAM 1.7-x.

4.1. One phase flow

First was done simulation without particles. The initial condition for velocity could be seen in the Figure 2. Dark blue color indicates zero velocity. The simulations ran for 0.5 s in order to allow development of turbulent structures in the domain. Then averaging was turned on and the simulations continued for another 1 s. This time was long enough to reach statistical steady state. The center of the coordinate system is positioned in the middle of the trailing edge. Results are compared with data from Fessler & Eaton (1999).

In the Figure 3 are depicted mean streamwise velocity profiles in various distances from the step. The full line represents LES simulation without particles, circles refer to the experimental data taken from [XXX] From these pictures could be noticed, that the core of the stream is not so inclined downwards as the experiment. This resulted in overprediction of the distance of the reattachment point behind the step. The reattachment point predicted by simulation is located at position $x/H = 8.2$, experiment predicts this point at position $x/H = 7.4$. Better prediction of the reattachment point could be achieved by using more advanced subgrid model, for example localised Smagorinsky model proposed by Ghosal et al. (1995).

The mean streamwise velocity fluctuations are shown in the Figure 4. Here can also be seen the lower inclination of the flow, the peaks are little bit shifted higher. However the difference
between simulation and experiment is not crucial and the LES simulation could be considered sufficiently accurate.

4.2. Particle-laden flow
The results of particle-laden flow are introduced in this subsection. The flow is laden with glass particles with diameter of 90 μm. The particles properties are summarized in Table 2.

| Table 2. | Particles properties |
|----------|---------------------|
| material | glass |
| diameter (μm) | 90 |
| density (kg.m⁻³) | 2500 |
| Stokes number | 3.0 |
| mass fraction (%) | 20, 40, 60 |

Particles are injected at the inlet to the region and their velocity was set equal to the velocity of the fluid in the position of the particle. The simulation started from the end of the unladen simulation. the averaging was turned off. When first particles reached outlet from the region,
the averaging was turned on and the simulations continued for another 1 s. The simulations were done for three different mass fractions of the particles in the flow.

The mean velocity profiles remain almost untouched by particles, the differences are very small and therefore are not presented here. The streamwise velocity fluctuations of the gas-phase with presence of the particles is depicted in the Figure 5. From here could be seen, that the particles has significant effect on the turbulence of the carrier phase.

The ratio of laden to unladen velocity fluctuations is in the Figure 6. The experimental data are for 20% mass loading particles. The simulations underpredict the magnitude of turbulence modification by particles. The turbulence modification increase with increasing mass loading of the particles. However the scaling of this modification with mass fraction appears not to be linear, which is in contradiction with experimental results.

5. Summary

The simulations of the particle-laden backward facing step flow were performed. For the description of the system fluid-particle was used Euler-Lagrange approach. The simulation was done using two-way coupling. This means, that the influence of particles on the fluid was

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**Figure 5.** Mean streamwise gas-phase velocity fluctuations with presence of 90 μm glass particles

**Figure 6.** Ratio of laden to unladen velocity fluctuations with presence of 90 μm glass particles
not neglected but was taken into account during simulation. The coupling between liquid and dispersed phase was achieved by adding special term to the momentum equation of motion. This term equals to the sum of forces acting on every particle. The concentration of the particles was chosen high enough to observe turbulence modulation.

For the solution of the fluid motion was used Large Eddy Simulation method. The motion of the particles was described by Lagrangian equations of motion. These equations was solved using second order Euler scheme. The simulations were done for three different concentrations of particles in the region.

It has shown, that approach used in this work tends to underpredict the turbulence modification by particles. Another simulations with another types of particles will be done in order to get better understanding of the turbulence modulation by the particles. It will be also implemented modification proposed by Garcia (2001), which includes the effect of the particles into subgrid model.

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