Proceedings of 31th IAHR Congress, Seoul, September 11-16, 2005.

LARGE EDDY SIMULATION OF OPEN-CHANNEL FLOW OVER A LAYER OF SPHERES

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ABSTRACT

The paper presents results of a Large Eddy Simulation (LES) of the flow in an open channel where the channel bed is roughened with one layer of spheres. The roughness height k, which corresponds to the sphere diameter d is *0.23* of the channel depth. The Reynolds number Re_t, based on the average friction velocity u_t and the channel depth h is approximately 2820. The flow configuration was selected to correspond to laboratory experiments of Detert (2005), which are currently in progress. Mean streamwise velocities from the LES are compared with the measured data and the distributions of the calculated turbulence intensities are evaluated by comparing them with empirical relationships for flow over rough walls suggested by Nezu (1977). The occurrence of low- and high-speed streaks is examined and their spanwise spacing is quantified. Moreover, sweeps and ejections are shown to occur as well as the amalgamation process i.e. ejection of fluid into the outer layer associated with vortex growth.

Keywords: Large Eddy Simulation; Turbulence; Rough beds; Open-channel flow; Coherent structures, Low-speed streaks, Vortex amalgamation.

1. INTRODUCTION

The dynamics of turbulent flow over smooth and rough walls is dominated by energetic three-dimensional organized (coherent), vortical structures. Over 4 decades of experimental work have been dedicated to the identification of the physical processes which govern these coherent structures, and much progress has been made in recent years due to the advances in measurement methods and in numerical simulation techniques associated with the growth in speed and capacity of modern supercomputers. Whereas the flow physics of coherent structures over smooth surfaces is understood fairly well (see the summary by Robinson, 1991), the flow over rough walls is still an area of active turbulence research. This is mainly due to the wide variety of possible wall roughness geometries and the fact that the details of the geometry influence the flow across the entire turbulent layer (Jimenez, 2004).

The mean velocity profile over rough beds differs considerably from the profile over a smooth bed since the surface drag is significantly larger when roughness elements are present. General functional relationships between the roughness geometry and the effects of the roughness on the mean flow are still not available. There are numerous studies attacking the problem, mostly based on the concept of relating the roughness geometry to a roughness function, $DU+$, expressing a downshift of the velocity profile in comparison to the velocity profile over a smooth bed. Further uncertainties arise in the quantification of the equivalent roughness height k_s, typically a fraction of the geometrical roughness height k, the origin of the wall normal coordinate y_o, which is usually determined empirically to optimize the fit to the logarithmic distribution, and last but not least the value of the von Karman constant k, which may not be universal for all roughness types.

The effect of roughness is of course not restricted to the mean flow properties. Flow visualizations and measurements (e.g. Grass, 1971, Grass et al., 1991, Defina, 1996 and many others) as well as recent Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) of flow over rough-walls (Leonardi et al., 2003, Stoesser and Rodi, 2004) indicate significant changes of the turbulence structure not only near the rough surface, but everywhere within the channel. The presence of organized structures near the walls, which are mainly responsible for the transport of momentum, heat and mass across the channel (Grass, 1971) is, irrespective of surface condition, established from these research endeavours. The streamwise velocity field near rough walls is, similar to the velocity field over smooth walls, organized into alternating narrow streaks of high and low speed fluid that are persistent, vary only slowly, and exhibit a preferential spanwise spacing (Defina, 1996). However, Leonardi et al. (2003) have shown that due to surface roughness, size and shape of the streaks change drastically as a result of enhanced momentum exchange between the near-wall region and the outer flow. Most turbulence production occurs when low-speed streaks are lifted away from the wall-layer in a violent ejection and during inrushing of high-speed fluid from the outer layer towards the wall. The complete cycle of lift-up of fluid, ejection and sweep motion makes up what is usually called the bursting phenomenon.

In this paper we present the results of a LES of open-channel flow over a bed artificially roughened with a layer of densely packed spheres. The main purpose of this study is to provide further insight into the turbulent flow over rough boundaries and to enhance the understanding of the effect of surface roughness on the mean and instantaneous flow. Temporal and spatial averaging is used to quantify the effects on the flow velocities and the three components of turbulence intensities. Furthermore, we investigate the flow and turbulence structure near the spheres and the associated occurrence of coherent flow structures. The spanwise spacing of low speed streaks is quantified and the processes of vortex growth and amalgamation are elucidated.

2. CALCULATION METHOD

The LES code MGLET, originally developed at the Institute for Fluid Mechanics at the Technical University of Munich (Tremblay and Friedrich, 2001), was used to perform the Large Eddy Simulations. The code solves the filtered Navier-Stokes equations discretised with the finite-volume method on a staggered Cartesian grid. Convective and diffusive fluxes are approximated with central differences of second order accuracy and time advancement is achieved by a second order, explicit Adams-Bashford scheme. The Poisson equation for coupling the pressure to the velocity field is solved iteratively with the SIP method of Stone (1968). The subgrid-scale stresses appearing in the filtered Navier-Stokes equations are computed using the dynamic approach of Germano *et al.* (1991). The no-slip boundary condition is applied on the surface of the spheres where the immersed boundary method is employed (Verzicco et al., 2000). This method is a combination of applying body forces in order to block the cells that are fully inside the sphere and a Lagrangian interpolation scheme of third order accuracy, which is used for the cells that are intersected by the spheres' surface to maintain the no-slip condition (Tremblay and Friedrich, 2001).

3. COMPUTATIONAL SETUP

The setup and boundary conditions of the Large Eddy Simulation were selected in analogy to flume experiments performed by Detert (2005), where spheres of *d=22mm* diameter were placed in one densely packed layer on the flat bottom. The water depth was set to *h=94mm* measured from the top of the spheres, which gives a roughness-height-to-depth-ratio of *d/h ˜ 0.23* (Figure 1). Streamwise velocities were measured by a 1D Acoustic Doppler Current Profiler (ADCP). The computational domain spanned *5h* in streamwise, *2h* in spanwise and *1h* in vertical directions, respectively and consisted of *16 x 9* spheres. A very high resolution grid consisting of *800 x 320 x 180* points for the computation domain and *42 x 36 x 100* points around one sphere was employed, which is approximately *46* million points in total. The grid spacings in terms of wall units were $?x^{+}$ ˜ *5* in streamwise direction and $?y^{+}$ ˜ *7* in spanwise direction. In the vertical direction the grid spacing was kept at a constant value of $?z^{+}$˜*2.5* from the bed to the top of the spheres and was stretched above the spheres towards the surface. A part of the grid, where only every 5th grid line is plotted, and the details of the grid around one sphere are shown in Figure 2. Periodic boundary conditions were applied in the streamwise and spanwise directions. A constant pressure gradient was maintained during the computation which yielded an average bulk velocity of u_{bulk}˜ *0.8 m/s* and an average shear velocity of u_t ˜ *0.07 m/s*. This gave a Reynolds number based on the channel depth *h* and bulk velocity u_{bulk} of Re_h ˜ *40,000*, a Reynolds number based on u_t and *h* of Re_t ˜ 2800 and a roughness Reynolds number based on u_t and *d* of Re_* ˜ 650. Assuming a similar sphere-diameter-to-roughness-height-ratio as found by Grass (1971) or Defina (1996), this corresponds to a dimensionless effective roughness height of $k_s^{+} \sim 420$.

4. RESULTS AND DISCUSSION

3.1. MEAN VELOCITIES

Figure 3 compares the time-averaged streamwise velocity profile in wall coordinates as obtained by the Large Eddy Simulations with the experiments of Detert (2005). Whereas the LES represents spatially averaged quantities, the data collected with the ADCP represent an average over the measurement volume being approximately half the size of a sphere. The overall prediction of the mean streamwise velocity is in very good agreement with the measured data. Also plotted is the log-law for rough walls i.e. $\frac{u}{u_t} = \frac{1}{k}\ln\left(\frac{z+\Delta z}{k_s}\right) + 8.5$, where a roughness length $k_s = 0.55d$ is taken in order to get the best fit to the measured and computed curves. The selected roughness length is similar to values suggested by Nezu ($k_s = 0.57d$) Defina ($k_s = 0.67d$) or Grass ($k_s = 0.68d\text{-}0.82d$). The zero plane displacement of $Dz=0.22d$ is evaluated with a least square fit and is of similar magnitude as reported by Grass et al. (1991) suggesting $Dz=0.22d$ for $k=12mm$ and $Dz=0.2d$ for $k=6mm$.

3.2. TURBULENCE INTENSITIES

The distributions of the three turbulence intensity components are plotted together with the empirical relationships suggested by Nezu (1977) in Figure 4. The overall agreement is fairly satisfying. In contrast to the flow over a smooth bed, the maximum value of turbulence intensities of the streamwise component is reduced by approximately 20%, which is a result of the wall roughness. Whereas most of the turbulence production over a smooth bed occurs in the buffer layer, this buffer layer disappears for the rough walls and consequently the turbulence is produced in another way. Our computed values are in excellent agreement with the measurements of Nezu (1977) and Grass (1971), who observed maximum turbulence intensities of around *2.1* for u'/u_* of *1.5* for v'/u_* and *1.1* for w'/u_* varying only slightly with the dimensionless roughness height k_s^{+}.

3.3. INSTANTANEOUS FLOW FIELD

Figure 5 presents an instantaneous distribution of the streamwise velocity fluctuation together with the fluctuating velocity vector (u'-w') in two selected x-z slices (indicated in Figure 1). It illustrates the presence of vortical motion, especially near the elements. Above the crest of the spheres, ejection events, where slower fluid is expelled away from the wall, and sweep events where slower fluid is pushed towards the elements, can be detected. Figure 5 further illustrates the exchange processes between the free surface flow and the interstitial region; it can be seen clearly that fluid plunges into the interstitial and moves back into the surface region at different locations.

Streaky structures are present just above the roughness elements as was shown e.g. by

Defina (1996) in his laboratory experiment with the help of dye. Figure 6 below shows the distribution of the instantaneous streamwise velocity fluctuation. The presence of high and low speed streaks alternating in the spanwise direction is visible. As was pointed out by several researchers in the past (e.g. Grass, 1991) the streak spacing should scale with the roughness height k_s. Grass (1991) used spheres with $k = 6mm$ and $k = 12mm$ and found streak spacing to roughness height ratios of $l/k_s = 3.82$ and $\lambda/k_s = 3.87$. However, Defina (1996) reported streak spacing to roughness height ratios just above the roughness elements of $l/k_s = 4.0$ being constant irrespective of Reynolds number. He further found that the spacing increases linearly with distance from the bed to ratios up to 20. In the present LES the average streak spacing ratio is l/k_s » 3.9 at a small distance (20 wall units) from the spheres. This corresponds very well with the findings of Defina and Grass.

Figure 7 presents an isosurface of instantaneous pressure fluctuations colour coded with the instantaneous streamwise velocity. The coherence of the flow structures and the vortex growth from the bed towards the surface can be seen clearly. This mechanism is known as vortex stretching by the local velocity gradient which provides the mechanism for the energy transfer from the free stream to the near wall region (originally suggested by Theodorsen, 1955). Figure 7 furthermore indicates the amalgamation process in which wall-region vortices are ejected and interact with the higher-speed outer region fluid during their growth and movement towards the surface.

4. CONCLUSIONS

The paper has presented the results of a Large Eddy Simulation of open channel flow over an artificially roughened bed. The calculated mean velocities showed excellent agreement with the measured data of Detert (2005) and conformity with the log law for rough walls. The predicted turbulence intensities were compared with the empirical relationships suggested by Nezu (1977). All three components found to agree well with these relationships and the data obtained by other researchers. The occurrence of low- and high-speed streaks was examined and their spanwise spacing is of similar magnitude as previously reported. Moreover, sweeps and ejections were shown to occur as well as the amalgamation process associated with vortex growth.

ACKNOWLEDGEMENTS

This work is part of the research project funded by the German Research Foundation (DFG) under project number JI 18/10-2. The authors would like to thank Dipl.-Ing. Martin Detert for the provision of the experimental data. The calculations were performed on the HP-XC machine of the Computing Centre at the University of Karlsruhe.

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FIGURES

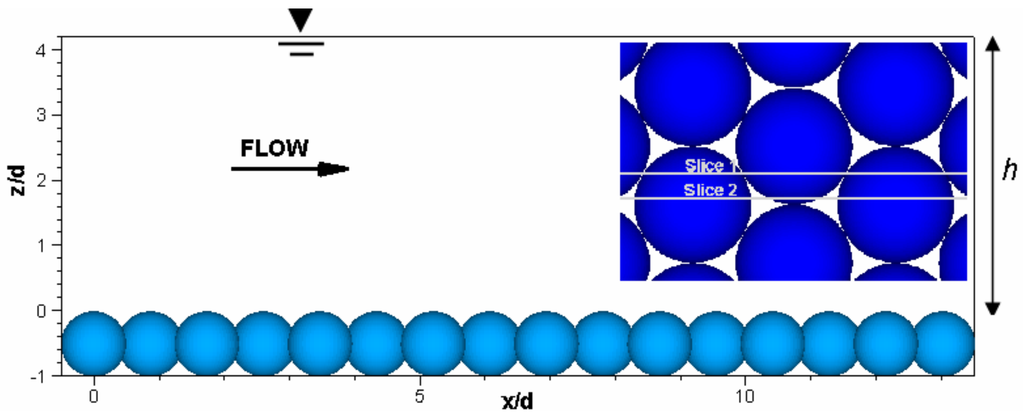

Fig. 1 Side view of the calculation domain with a top view on the packing of the spheres

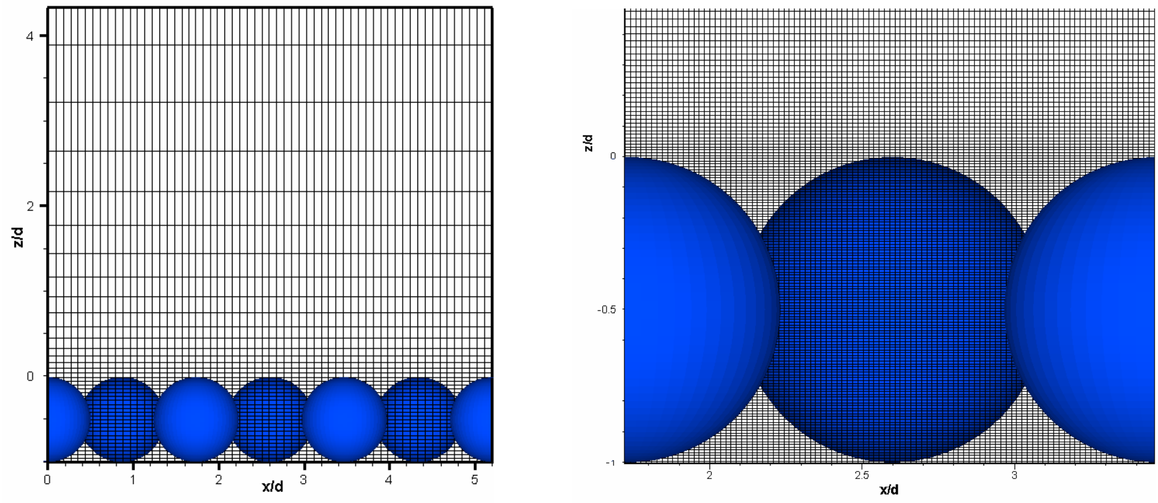

Fig. 2 Part of the computational grid (left) and details of the grid around one sphere (right)

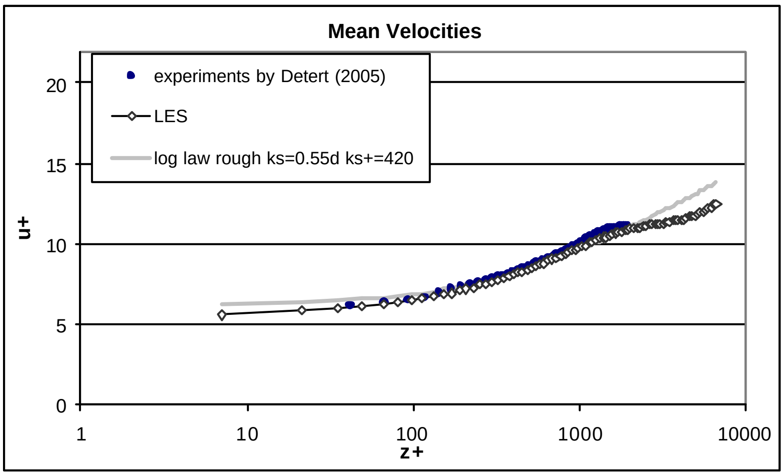

Fig. 3 Comparison of time averaged streamwise velocities to experiments and to the log law

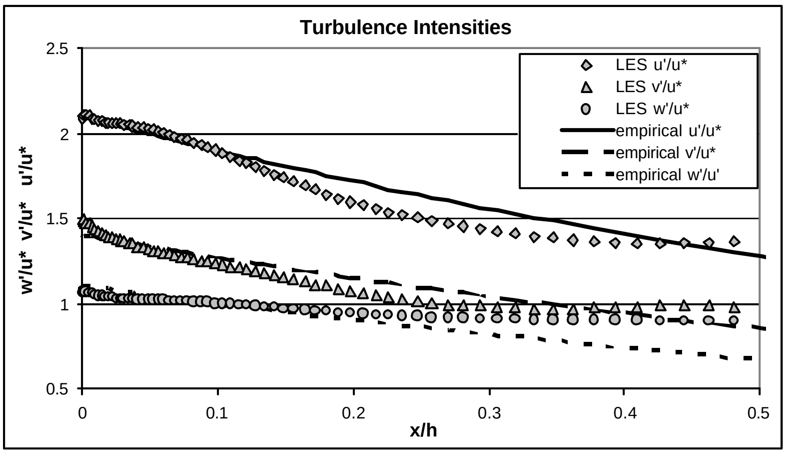

Fig. 4 Comparison of turbulent fluctuations to empirical relationships of Nezu (1977)

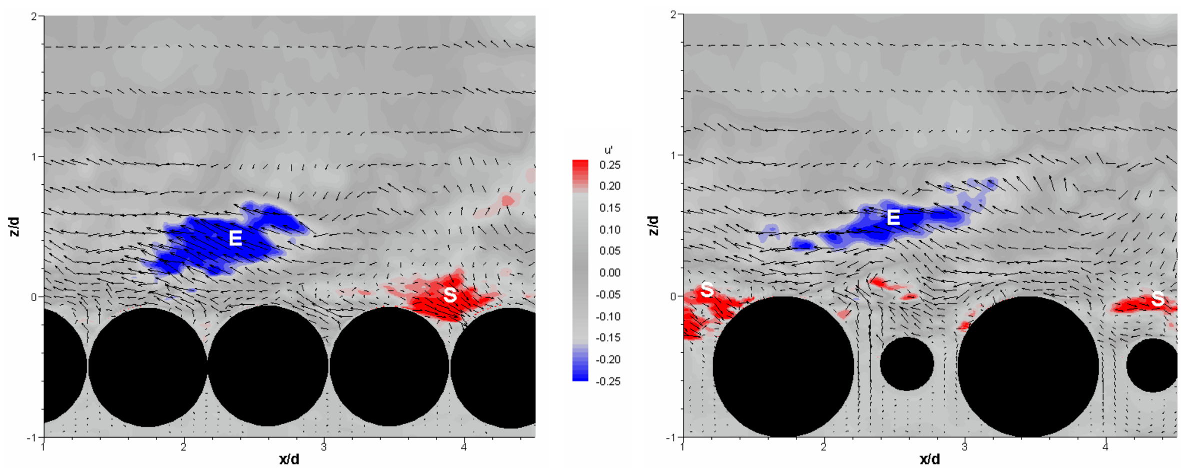

Fig. 5 Instantaneous streamwise velocity fluctuations and fluctuating vectors in two selected longitudinal slices as indicated in Figure 1 – Slice1 left, Slice2 right

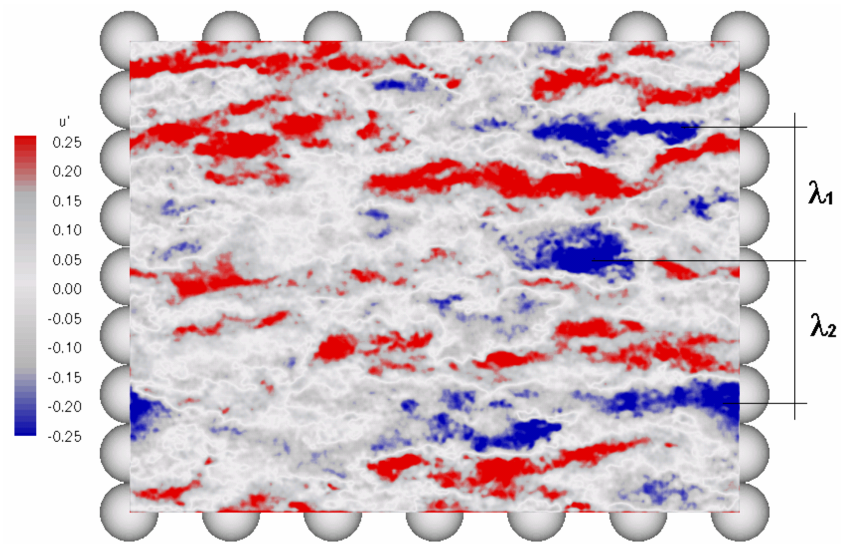

Fig. 6 Instantaneous streamwise velocity fluctuations in a x-y plane just above the spheres

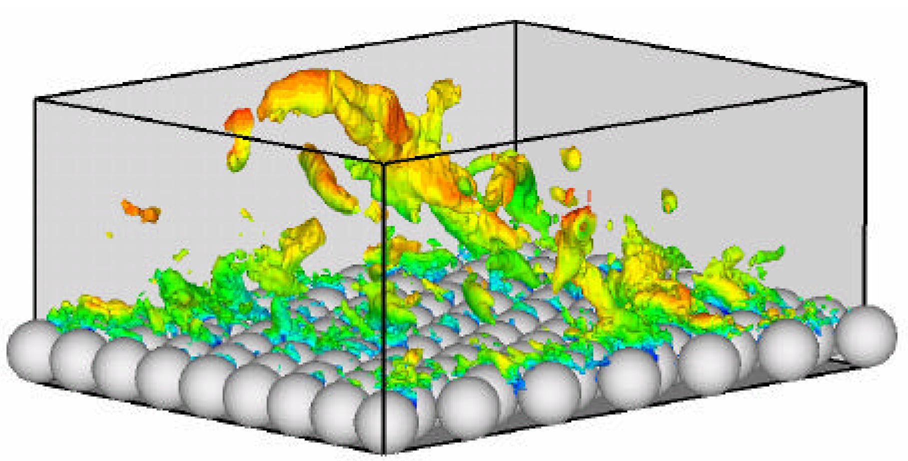

Fig. 7 Isosurfaces of instantaneous pressure fluctuations colorcoded with the instantaneous streamwise velocity