Measurement of flows in randomly packed beds using the Particle Image Velocimetry

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Abstract Randomly packed beds are frequently used in the chemical and process industry as reaction, separation or purification units. The exact determination of the flow field insides the beds is of fundamental interest in order to design such reactors and to predict their characteristics. In the present paper, the particle image velocimetry (PIV) is employed to measure the velocity distribution in the flow through the void space between randomly packed spheres. For the chosen regime of Reynolds number Re_D = 10 –50, the flow is in steady state. However, inertial effects become important and a boundary layer type flow around the spheres establishes. In order to permit undisturbed optical access into the test section a matching of the refractive indexes of the fluid and the material of the embedded spheres and enclosures is realized. The data obtained are intented to provide a reference for numerical simulations. Therefore, particular attention was paid for the determination of the inflow velocity profiles entering the test section. The results indicate that the PIV method can be efficiently used in order to provide field data of velocity with realtively low effort compared to MRI or LDA methods.

1. Introduction

In chemical industry, tubular fixed-bed reactors with randomly placed particles can be found in various applications such as separation and purification units or to enhance catalytic surface reactions. The design of these reactors is usually based on simplified models such as the plug flow assumption which fails for large ratios of particle to tube diameter (d/D > 0.1) due to non-uniformities of the porosity distributions and the velocity field. Therefore, modeling of flows in this type of porous media is a topic of continuous interest since long time. Already in 1949, Ergun [1] has evaluated the fluid flow through randomly packed columns. Daszkowski and Eigenberger [2] have evaluated the effect of fluid flow on heat transfer and chemical reactions, Bey and Eigenberger [3] provided modifications of classical design concepts by introducing variable porosity profiles. However, the modeling of these flows is based on empirical parameters which have to be obtained experimentally after evaluating velocity fields in the bed. Due to the complexity of the geometry, this is not possible with classical methods such as pitot probes or hot wire anemometry. Therefore measurements of velocity profiles have been done by Saunders and Ford [4] right downstream the packed bed. Direct measurements of the pore velocity have been done by Klar et al. [5], who obtained the velocity using a minituarized 3D particle tracking velocimetry (PTV) system incorporated in an artificial pore. This method is limited by the size of the measurement probe. Apparently, non-intrusive measurements methods may provide more detailed results. As example, three dimensional results have been obtained by Kunyasu et al. [6] using the tagging method and the magnetic resonance imaging (MRI) technique. However, MRI is limited to non-metallic and non-magnetic materials and requires a substantial investment in equipment. The laser Doppler method (LDA) may be used in transparent test sections after carefully matching the refraction indexes of the fluid and of the embedded spheres and confining tube. Since LDA is an interferometric technique, it is very sensitive to variations of the refractive index and it provides

only point data. Thus, a substantial effort has to be spent in order to guarantee a perfect matching [7]. In this paper, the particle image velocimetry (PIV) is used since it allows determining the velocity field along a plane and it is less sensitive to differences of the refractive indexes.
The intention of this work is to provide reference data that allow a direct comparison with results of numerical simulations. Therefore, special attention was paid for the design of the test section and of the specification of the velocity profile of the fluid entering the test section. This allows prescribing exactly the same boundary conditions, when attempting to compute the flow in the bed using numerical methods. The design of the test section itself was supported by numerical simulations using a CFD tool.
The present paper is organized as follows: After this introduction, the experimental set up is explained in detail. Experimental results are presented in chapter 3 for two different sphere sizes. Finally, conclusion and an outlook are given.

2. Experimental procedure

The objective of the present paper is to accurately measure the velocity field in laminar and steady flow through the void space of a packed bed using PIV. The setup consists of the test section, a RPM-regulated pump, venturi nozzle, temperature control and an expansion tank as shown in figure 1.

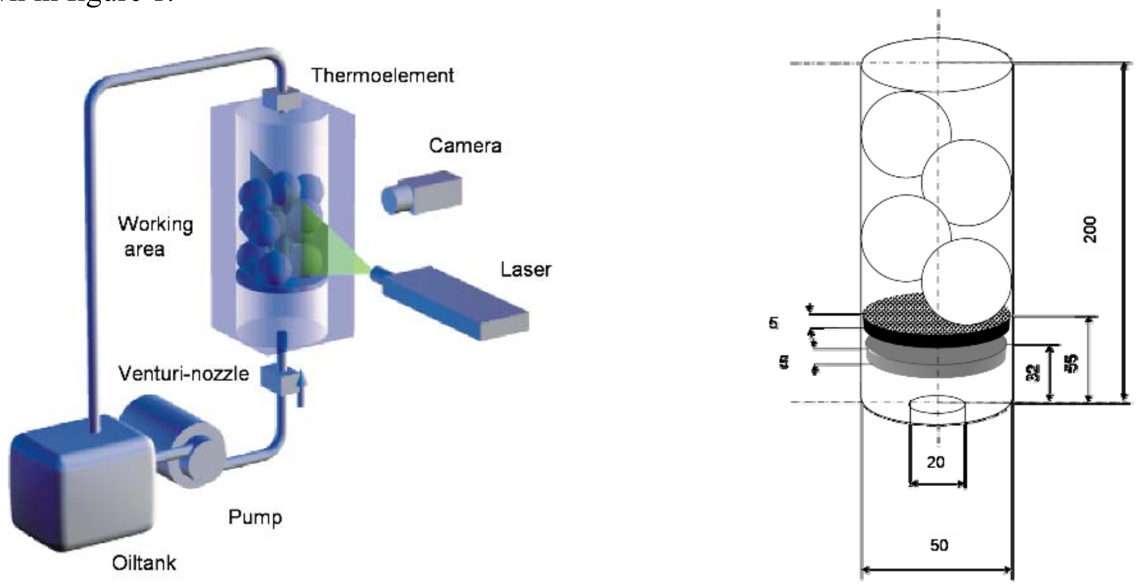
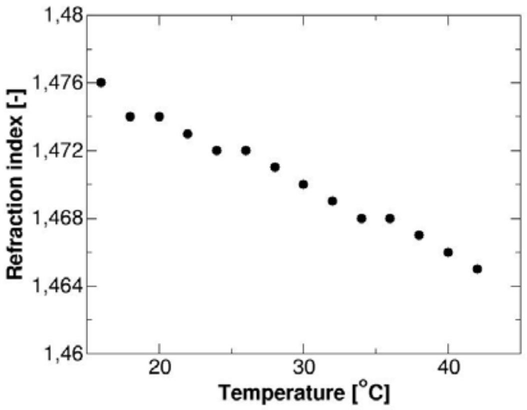


Figure 1: Experimental setup and detail of the working area, dimensions in mm.

An ILA 2D PIV system is used consisting basically of a 15 mJ dual cavity Nd:YAG-laser, a PCO Sensicam QE CCD camera (resolution 1376 × 1040 pixels) and a PC with control and analysis software. The test section itself contains randomly placed spheres confined by a cylindrical tube with 50 cm inner diameter. Two different sphere diameters (9 and 30 mm) are used. The fluid is a naphten basic medical white oil (Shell Ondina 927) with fluorescent tracer particles (Rhodamin coated particles with 10 nm diameter).
Since an optical measuring technique is used, optical access into the packed bed without distortion of the light path is required. Therefore, the fluid as well as the materials of embedded spheres and confining wall is carefully selected according to their refractive index. In the present setup, the solid parts are manufactured in quartz glass. The confining cylinder is embedded in a rectangular container filled with oil, as indicated in figure 1. Thus, the light enters the test section normal to the outer confining walls. No refraction occurs when the light sheet enters the embedded cylinder

outside of its midplane. The refractive index of the glass was measured using a white light immersion method and found to be in the range $n_G = 1.470 - 1.472$. The temperature dependence of the refractive index was determined using an Abbe-refractometer. The results are shown in figure 2, indicating that a fluid temperature ranging between 25°C and 30°C should be established. A more precise matching is obtaining using the Christiansen-filter by measuring the transmission of light in a mixture of grounded glass particles and the oil. The results in figure 2 confirm that at temperatures around 28.6 °C the best matching is obtained. In the setup the temperature was controlled and maintained at this value during the experiment.



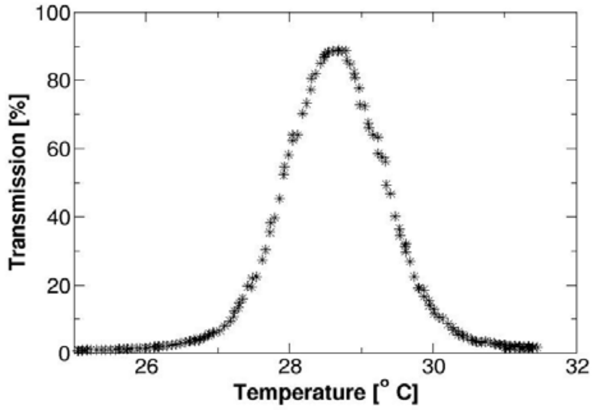


Figure 2: Temperature dependence of the refraction index of oil (Shell Ondina 927), Optimal temperature for the accommodation of the refraction indexes.

In the experimental setup, a well defined constant velocity at the entrance of the packed bed should be imposed in order to facilitate the definition of boundary conditions for accompanying numerical simulations. Thus, special attention was paid for the uniform distribution of the velocity immediately upstream of the test section. This is achieved using a baffle and a flowstraightener consisting of a perforated plate. An analogy between the flow in capillaries and the permeability of the porous media is employed to specify the flow in this region [8]. A sketch of the arrangement is shown in figure 1. The permeability and porosity of the flowstraightener is optimized using numerical computations of the flow in the entrance section. Finally, a porosity of $\varepsilon = 0.5$ and a pore diameter of 1 mm were selected as an optimum choice, but because of the limited technical feasibility, a flowstraightener with a porosity of $\varepsilon = 0.3$ and a pore diameter of 1.5 mm has been built.

3. Results and discussion

Results are obtained for the flow through two different packed beds consisting respectively of spheres with 9 mm and 30 mm diameter. To examine the homogeneity of the flow at the entrance of the test section, additional measurements are performed without packed bed. In all cases, the volumetric flux is 0.2 Liter/s. This corresponds to a Reynolds number $Re_D = 15$ and $Re_D = 45$ depending on the diameter of the spheres. Thus, a steady and laminar interstitial flow is expected [8]. However, inertial forces start to affect the flow, i.e boundary layers around the spheres become more pronounced. Eventually, flow separation in the voids may occur. Downstream of the flowstraightener the velocity is basically constant, except in the region close to the confining cylinder.
In a first step of the experiment, measurements are obtained for the midplane of the packed bed, parallel to flow direction. In figure 3, the corresponding velocity distribution for 30 mm spheres is

shown. In figure 4, details of the velocity are presented.

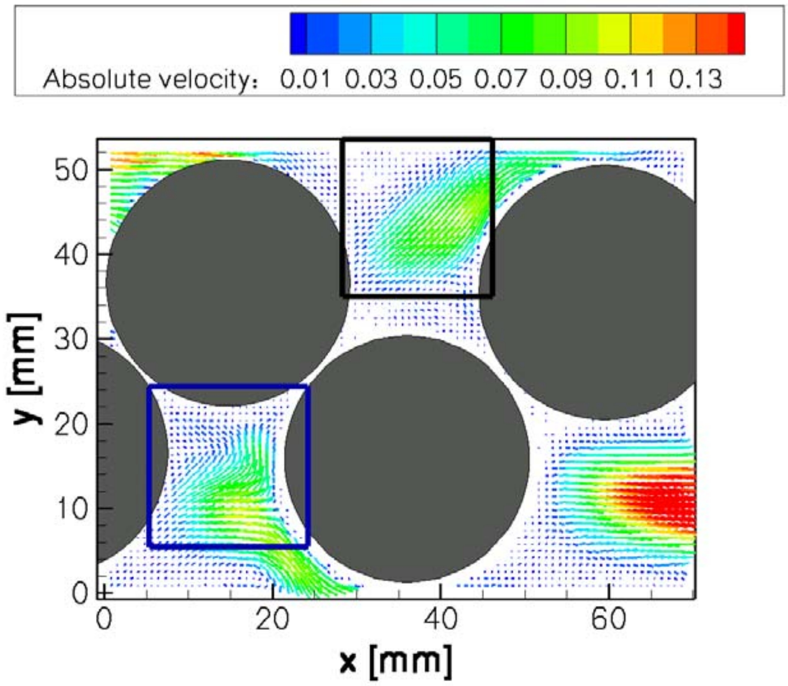


Figure 3: Velocity profile in the midplane of the tube filled with 30 mm spheres.

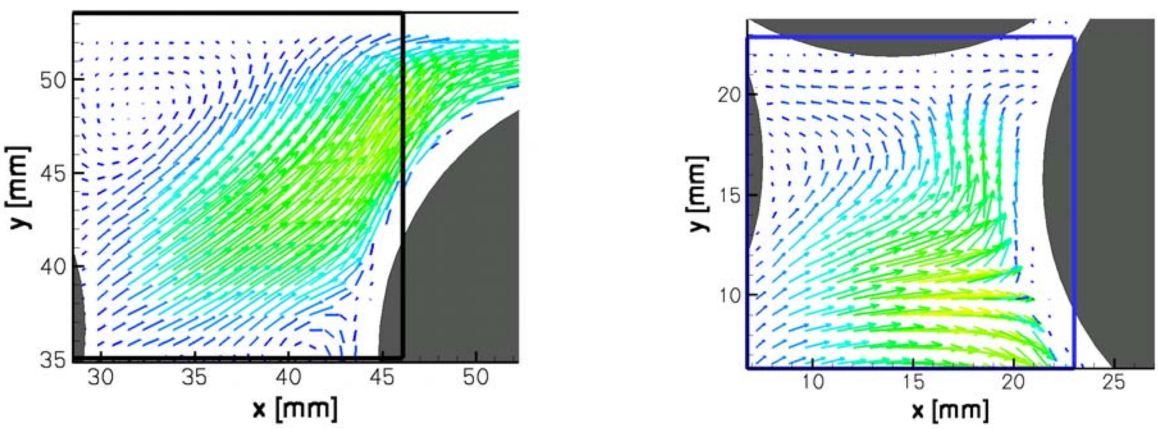


Figure 4: Details of the velocity profile in the midplane of the tube filled with 30 mm spheres.

Finally, in figure 5 the velocity distribution in the packed bed consisting of 9 mm spheres is presented. In figure 6 details of the velocity distribution are shown, indicating that recirculation doesn't occur. Due to the lower porosity of this configuration, significantly higher velocities are observed.

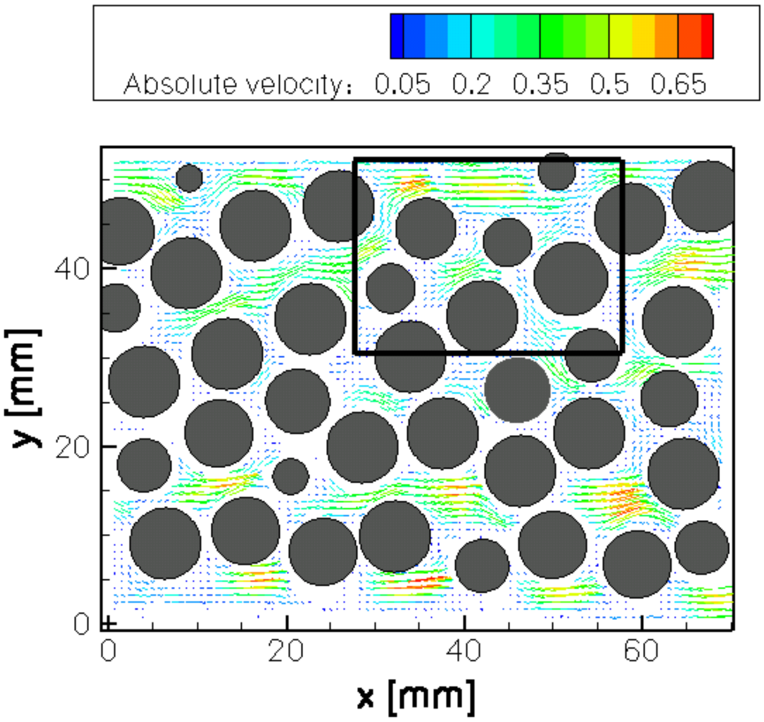


Figure 5: Velocity profile in the midplane of the tube filled with 9 mm spheres

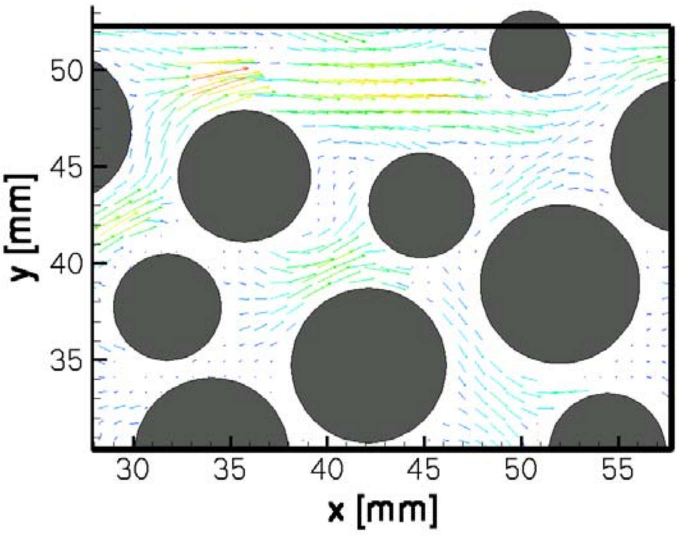


Figure 6 Detail of the velocity profile in the tube filled with 9 mm spheres

The goal of the second part of the project is the determination of the axial velocity field in the entire fixed bed. This velocity field in three dimensions is reconstructed from two dimensional measurements taken along various meridian planes. The latter are obtained by rotating the inner cylinder containing the embedded spheres in increments of 10 degrees. Using this approach allows to obtain only the axial component of the entire velocity three dimensional velocity field because of the two dimensional PIV setup. By averaging the velocity in the mean flow and in the circumferential direction, the mean axial velocity as function of the radius is obtained. In figure 7, for the large sphere bed, the axial velocity is presented as topographic plot along five planes normal to the mean flow direction. The large spikes close to the confining wall indicate the channeling effect. The mean axial velocity for the same configuration is presented in figure 8.

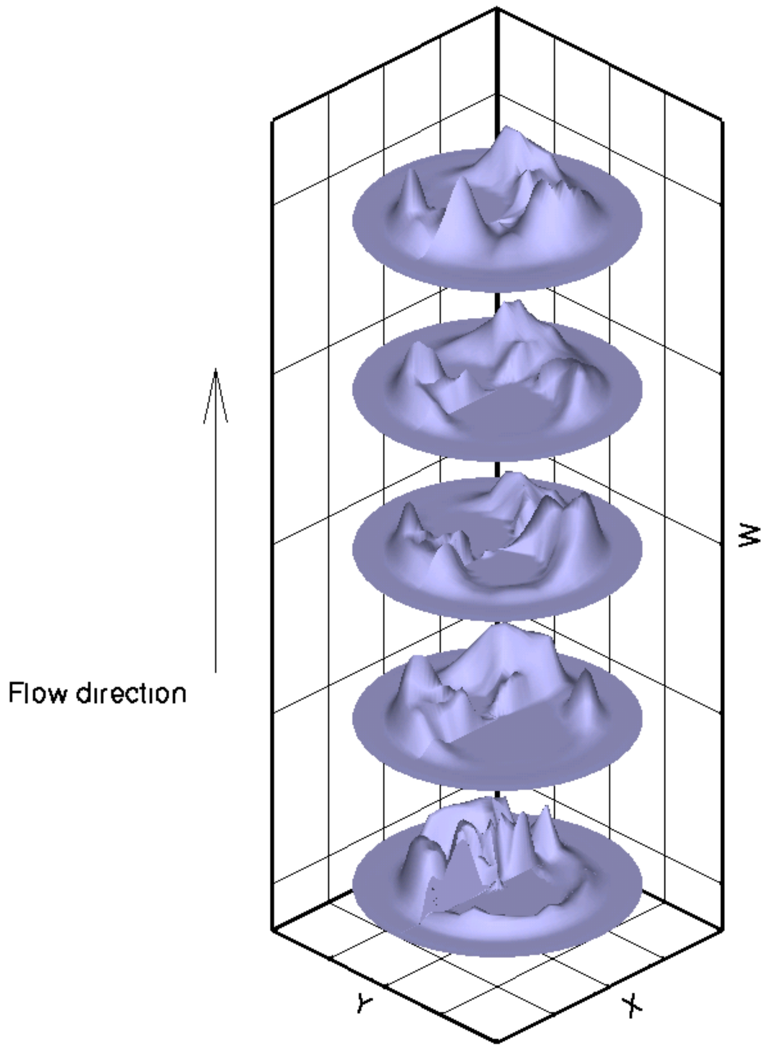


Figure 7 Axial velocity at different heights of the tube filled with 30 mmspheres

In figure 8 the velocity has been averaged over the height of the fixed bed and the sections at different angles and plotted versus the normed radius.

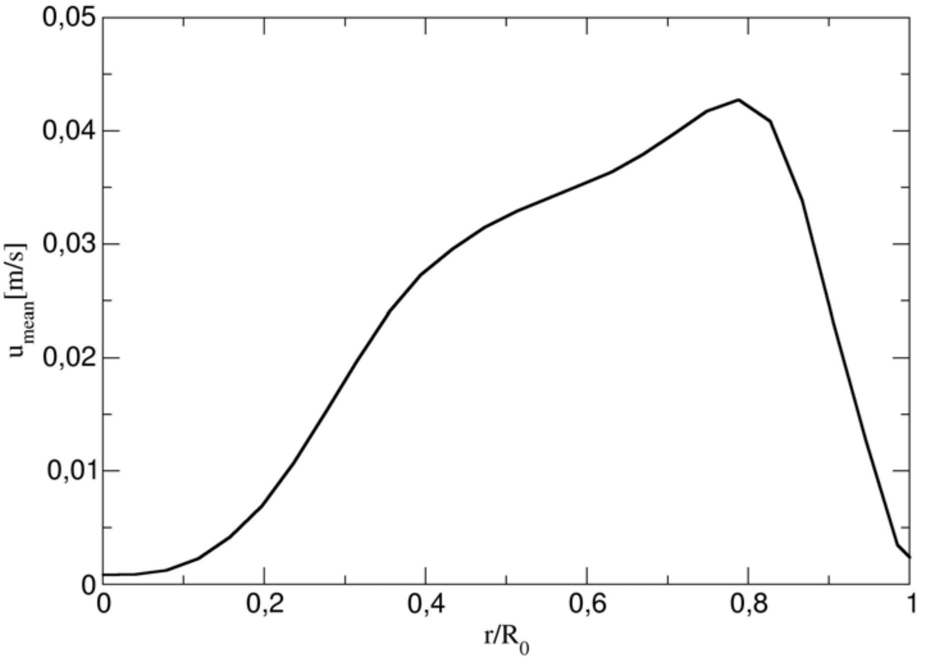


Figure 8: Mean axial velocity in the tube filled with 30 mm spheres

In the experiments with the large spheres, the tube is filled with 4 spheres and the peak lies in the void between the first sphere (lowest sphere) and the third sphere, and the second and the fourth sphere respectively. This void is produced through the fact that the first and the third sphere lie in the same side of the tube wall and the other spheres on the opposite sode, creating the void.

The velocity in the tube filled with small spheres is higher as in the tube filled with big spheres because of the channeling effect due to the lower porosity. The correlation between the location of the spheres and the velocity peaks is more complex. There are more peaks, due to the channeling effect between the spheres, but additionally high velocities are located at the borders caused through the higher porosity close to the wall. The plot of the average veloicty over the radius shows clearly that in the middle of the tube lower velocities are found. This is due to the fact that the diameter of the tube is an uneven multiple of the diameter of the spheres, so that for each layer the middle of the tube is always occupied through a sphere, avoiding the passage of the fluid. Because the spheres do not completely cover all the cross section (the sum of all the spheres diameters over the cross section is less than the total inner diameter of the tube), there is a void between the wall and the one of the outer spheres of the layer, justifying the variation of the height of the peaks at the wall. Throug this extra void, higher velocity are produced and the stream close to the wall increases. The location of this effect alternates with the layers.

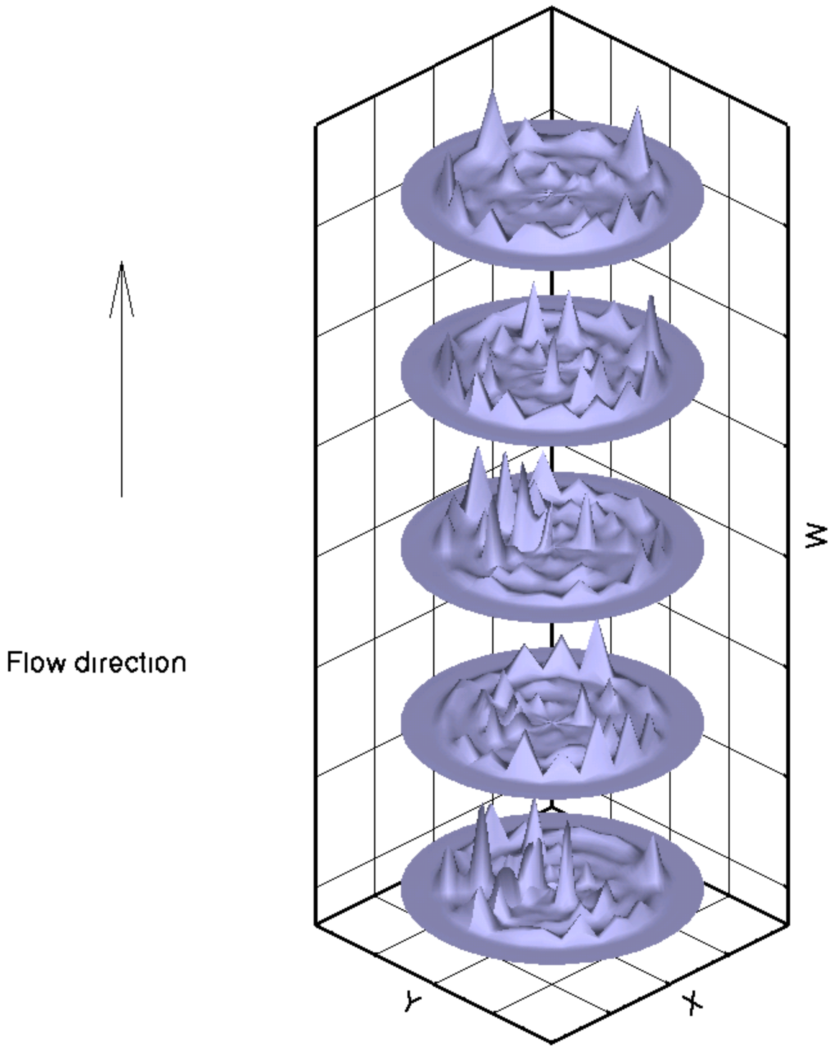


Figure 9: Axial velocity at different heights of the tube filled with 9 mm spheres

The average velocity over the height of the tube reveals, as plotted in figure 10, that the highest velocities are located at the wall.

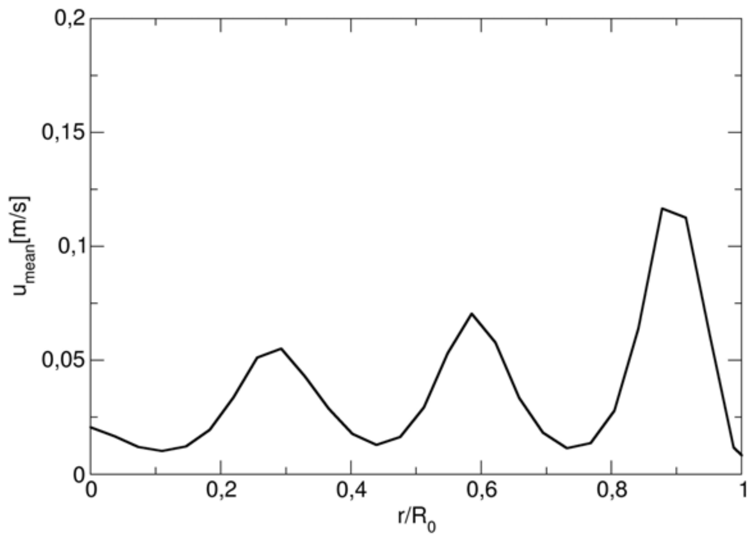


Figure 10: Mean axial velocity in the tube filled with 9 mm spheres

4. Conclusion

In the present paper, the PIV method is used to examine the interstitial flow field in packed bed of spheres. Using materials with matching refractive indexes, an optical access of the void space between the spheres and quantitative measurements of flow velocity can be achieved. This demonstrates that the PIV method may be used to examine the flow in packed beds and geometries with similar complexity. Thus, PIV is an alternative to more expensive and laborious measuring techniques such as MRI or LDA. For the reconstruction of the whole velocity field, measurements with two cameras (stereo-PIV) are planned.

4. Literature

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