Summer 6-24-2014

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Proceedings of the 5th International Conference on Porous Media and its Applications in Science and Engineering
ICPM5
June 22-27, 2014, Kona, Hawaii

THREE-DIMENSIONAL FLOW IN A SPHERE-PACKED PIPE BY DIGITAL-HOLOGRAPHIC-PTV AND NUMERICAL SIMULATION

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ABSTRACT
In present study, high time-resolution flow field measurement in a sphere-packed pipe (SPP) is performed by the digital-holographic particle-tracking velocimetry. The visualization technique is carried out by a refractive index-matching method using a sodium iodide (NaI) solution employed as a working fluid. Hologram fringe images of particles behind the spheres can be observed, and the particles' positions can be reconstructed by a digital hologram. Consequently, 3-D velocity-fields around the spheres are obtained by the reconstructed particles' positions. In addition, numerical simulation of a sphere-packed pipe flow with Immersed Boundary technique is carried out to compare with the experimental value. In comparison with averaged velocity profiles, the experimental value is in good agreement with the numerical value quantitatively.

INTRODUCTION
A basic heat transfer promoter such as packed beds of spheres [2] is one of the technology of the promotion of heat transfer by using the turbulent mixture. Yuki et al. [8] performed PIV visualization to understand the complex structures in a sphere-packed pipe (SPP)[2]. The PIV experiment was conducted using a matched refractive-index method [1] with NaI solution as the working fluid. They found a meandrous bypass with high-flow velocity due to the wall effect. Their visualization was a 2-D velocity field, and based on its information the flow structure was realized. Recently, we carried out 3-D visualization of digital holographic PTV [5][6] to understand the complex flow structures in a sphere-packed pipe (SPP) by using a refractive index-matching method with a sodium iodide (NaI) solution used as a working fluid[7]. This solution when used as working fluid is deliberately chosen to be able to adjust its refractive index to match to that of the acrylic sphere with an index of 1.49. In the present study, numerical simulation of a sphere-packed pipe flow with Immersed Boundary technique is carried out to compare with the experimental value.

NOMENCLATURE

f	=	Body force
u	=	Velocity
p	=	Pressure
Greek Symbols		
ρ	=	Density
ν	=	Dynamic viscosity

SIMULATION

Three-dimensional Navier-Stokes equation with immersed boundary technique [3] requires an additional term to account for flow fields of complex geometries such as found in a sphere-packed pipe flow addressed in this study. In this calculation, the equations are expressed as follows:

$$\nabla \cdot \mathbf{u} = 0 \qquad (2)$$

$$\frac{d\mathbf{u}}{dt} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \delta(x-b)\mathbf{f} \qquad (3)$$

Where, the additional term in eq. (3) is the body force $\mathbf{f}$ multiplied by a local fuction $\delta(x-b)$, where the function $\delta(x-b)$ takes a unit value when x is equal to b at the wall boundary. The additional term in the Navier-Stoke euation is derived from immersed boundary technique; the term account for the representation of non-slip walls when the limit value is exceeded. Thus, artificial wall boundary condition can be created when the function $\delta(x-b)$ in the additional term is incorporated into the flow field equation. These terms are adopted for three-dimentional momentum equation. The flow geometry is genereated by a unit value in the formation of the sphere-packed pipe flow. Figures 1 shows the sphere-packed pipe flow. The distribution of the flow geometry is defined by the regular size spec of a sphere-packed pipe flow. The both computational boxes are constructed by 256 x 128 x128 gird points.

Figure 1: Computational geometry in a sphere-packed pebble derived by an immersed boundary technique

EXPERIMENT

Acrylic spheres with diameters of 8mm were then packed into the observation region thus forming a SPP structure as shown in Fig. 2. To validate the flow state for this pipe setup, present data without pebbles is compared with DNS data by Satake et al. (2000) [4]. The velocity profiles obtained by the present experimental data are in good agreement with that of the DNS data. Therefore, the flow state without pebbles is a fully developed turbulent flow, and this pipe setup enables a complete turbulent flow. In this experiment, a Nd:YLF laser (λ= 527 nm) was used as a light source out-putting a pair of laser pulses at a repetition rate of 1 kHz, and a pulse delay of 100 μsec. The laser beam was then expanded to illuminate the center of a test section. For this test, 40-micron silica spherical particles were used. Here the working fluid was a 63 wt % NaI solution that was designed to match the refractive index of the working fluid to the refractive index of the acrylic sphere with an index of 1.49. An observation region was created by hollowing out a 16-mm-diameter cylindrical domain inside an acrylic resin box (height = 20 mm, width = 160 mm, and depth = 20 mm). At this time, two spheres at the downstream region were fixed by a metal wire mesh not to flow out and the other spheres were arrayed regularly. Since diameters of the cylindrical domain and the spheres have high-accuracy, all of spheres did not move in the process of measurement. The observed area was more than 6 layers of a sphere pair away from the mesh. A 62.9 wt % NaI solution at 21 °C matched its refractive index to 1.4905. This combination of the concentration and temperature resulting in a refractive index of 1.4905 has already been proven as shown in ref. [7]. The visualization of the flow field is conducted at a Reynolds number (Re_d=$U_d\, d$ / ν) of 700, where U_d and d stand for inlet velocity and sphere diameter. The mean inlet velocity, which is equivalent to the superficial velocity in the SPP, is 0.154 m/s. When the refractive indices between the working fluid and the sphere are matched, the hologram fringe image of the particles behind the sphere can be observed, and the particle positions can be reconstructed by a digital hologram. In this work, the hologram fringe images were captured through a high-resolution digital CCD camera (IDT NR5S2) without a lens with a resolution of 2336 x 1728 (7 μm / pixel). This technique captured the images at 1 k Hz, and used 1024 x 1024 pixels in the full imaging area. The camera and the laser were synchronized by a pulse generator, and the exposure time was set to 100 μs. The system was design to work with 2169 frames using the camera memory with a sampling rate of 1 k Hz.

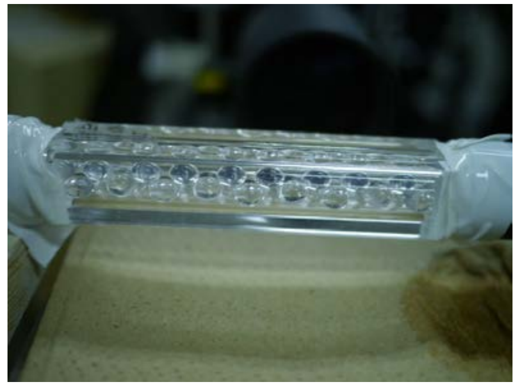

Figure2: Pebbles in the observation region

3 Result and discussions

Figure 3 shows velocity vector for numerical simulation on the cross section defined by half of the pipe diameter. The velocity was accelerated between the pebbles. The velocity value in the center region was highest. Figure 4 shows hologram images of pebbles and particles in NaI solution. The hologram fringe images of the particles behind the pebbles are observable. To set 1KHz sampling, the hologram fringe images were captured 1024 x 1024 pixels from 2336 x 1728 pixels in the full imaging area of a high speed camera.

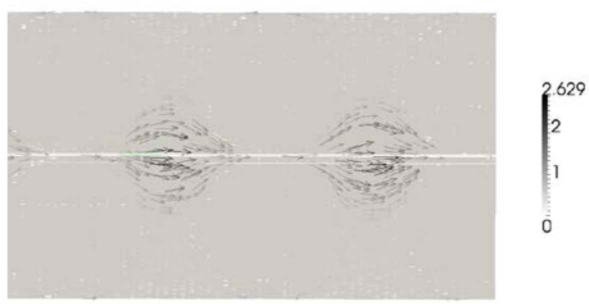

Figure 3: Velocity vector for numerical simulation on the cross section defined by half of the pipe diameter.

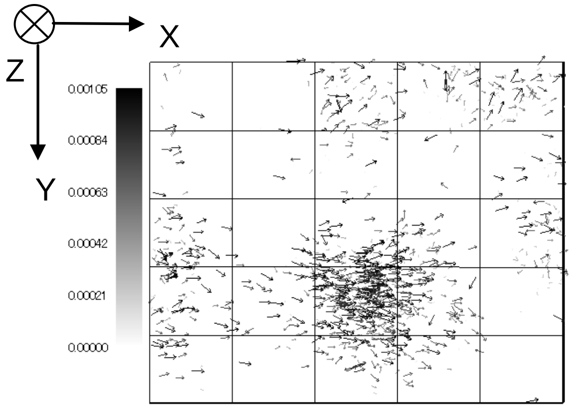

Figure 4 : Velocity vectors for experiment in the x-y plane

It can be seen that the flow is mainly moving in a stream-wise direction, and the velocity vectors have around the pebbles. The velocity has a similar behavior compare with the velocity by the simulation.

CONCLUSIONS

In this work, the numerical simulations with geometries similar to the geometries of the corresponding experiment in a packed pebble flow are performed by the immersed boundary technique where the numerical simulations and the experiments are compared using the same flow parameters. Three-dimensional velocity vectors of the experiments were in agreement with that of the numerical simulation.

ACKNOWLEDGEMENT

This research was partially supported by Program for Development of Strategic Research Center in Private Universities supported by MEXT (2011).

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