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Three-dimensional flow measurement of a sphere-packed pipe by a digital hologram and refractive index-matching method

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ABSTRACT

Molten-salt used as a coolant in fusion reactors plays a significant role in the design of advanced reactors. Investigation of thermal behavior is necessary in an actual environment of a facility where heat transfer enhancement takes place under a high Pr number fluid flow such as in case of FLiBe. For the development of a facility, it is necessary to be able to monitor fluid motion of a basic heat transfer promoter such as a sphere-packed pipe (SPP). In the present study, to discern the complex flow structures in SPP, digital holographic PTV visualization 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. The velocity between pebbles is found to be faster than that in other regions.

1. Introduction

An advanced power extraction (APEX) study [1] has been conducted in the US regarding the utilization of FLiBe as a coolant. Moreover, those working in the area of inertia fusion energy (IFE) [2] view the utilization of FLiBe-free surface flow as a means of chamber protection and hence it is important to investigate the thermo-fluid feature of molten-salt FLiBe flow in both Magnetic Fusion Energy (MFE) and IFE devices. In general, a high Prandtl number (Pr) fluid like FLiBe (Pr = 30) has less thermal diffusivity, thus, a high Pr fluid flow has less heat transport capability because of low thermal conductivity and very thin thermal boundary layer. Therefore, it is important to develop the technology of the promotion of heat transfer by using the turbulent mixture in such a thin thermal boundary layer. For the development of the facility, it is necessary to monitor the fluid motion of a basic heat transfer promoter such as packed beds of spheres [3]. Yuki et al. [4] performed PIV visualization to understand the complex structures in a sphere-packed pipe (SPP) [4]. The PIV experiment was conducted using a matched refractive-index method [5] 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. In the present study, digital holographic PTV [6,7] of 3-D visualization to understand the complex flow structures in a sphere-packed pipe (SPP) is carried out by using a refractive index-matching method with a sodium iodide (NaI) solution used as a working fluid. 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.

2. Visualization of a sphere-packed pipe flow

2.1. Refractive-index adjustment of the sodium iodide solution

The method of eliminating refraction problems in liquid flow is to match the refractive index of an object in a liquid with the refractive index of the liquid surrounding the object. In our case, we used NaI solution as a working fluid. The reason for choosing NaI is that it uses pebble spheres made from the acrylic resin. Fig. 1 shows the refractive-indices of working fluids at different concentrations as functions of temperature (T = 20–45 °C), as measured by a temperature-controlled Abbe's refractometer. Temperature, concentration, and refractive index are mostly in a linear relationship, and we presupposed a near normal temperature of 20 °C as the operating temperature for this result.

A test structure (height = 40 mm, width = 22 mm, and depth = 16 mm) shown in Fig. 2, was made of an acrylic resin. The working fluid shown in Fig. 2(a) was pure water; and the working fluid shown in Fig. 2(b) was a 63 wt% NaI solution. Both

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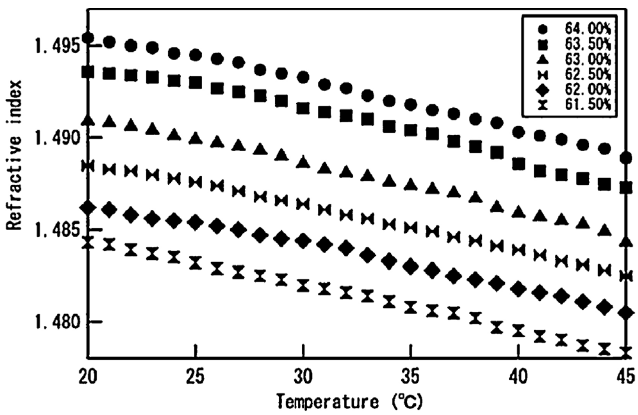

Fig. 1. The relationship between refractive-index and concentration of working fluid.

the pictures show pebble spheres in those fluids. The solution in Fig. 2(b) enables a clear view through the sphere. When the refractive indices between the working fluid and the pebble sphere were matched, the pebble sphere became invisible.

2.2. Experiment apparatus and details of the test section

Fig. 3 is a schematic of the experimental setup that shows the location of a laser beam single source. To validate the flow state for this pipe setup, present data without pebbles is compared with DNS data by Satake et al. [8]. 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 μs. 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). Acrylic spheres with diameters of 8 mm were then packed into the observation region thus forming a sphere-packed pipe (SPP) structure as shown in Fig. 4.

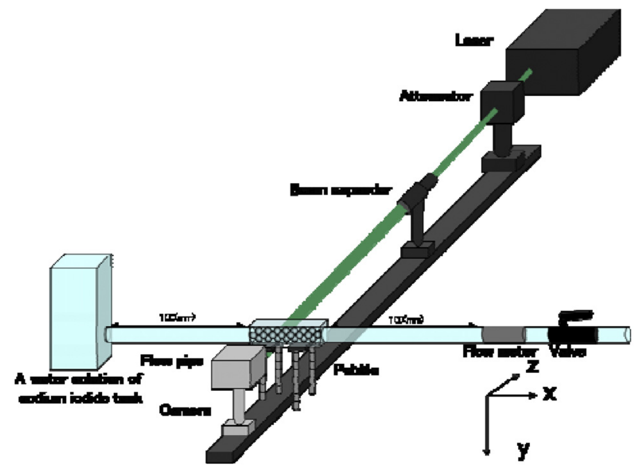

Fig. 3. Experimental apparatus.

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 the 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 an refractive index of 1.4905 has already been proven as shown in Fig. 1. The visualization of the flow field is conducted at a Reynolds number ($Re_d = U_d \cdot d/\nu$) of 700, where U_d and d stand for inlet velocity and sphere diameter. The mean inlet velocity, which

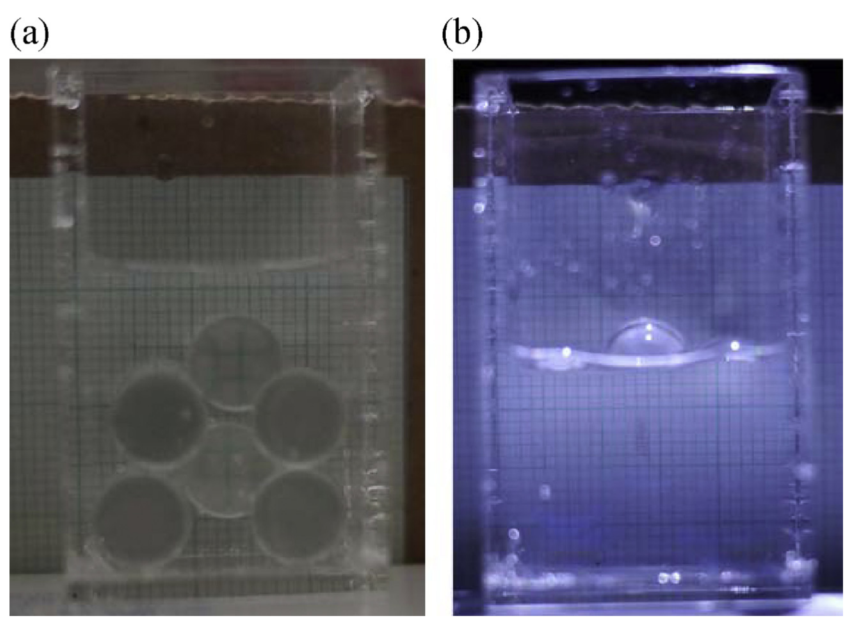

Fig. 2. Photo of pebbles in an acryl box: (a) pure water and (b) a 63 wt% of NaI solution.