Simultaneous Measurement of Particle Motion and Temperature in Two-Dimensional Fluidized Bed with Heat Transfer[†]

Takuya Tsuji*, Takuya Miyauchi, Satoshi Oh, Toshitsugu Tanaka
Department of Mechanical Engineering, Osaka University¹

Abstract

Fluidized beds are widely used in industrial processes concerned with heat transfers. In the present study, a measurement technique based on the coupling between particle tracking velocimetry (PTV) and infrared thermography (IT) measurement is proposed. By using the technique, the motion and the temperature of individual particles and its relations with the characteristic flow structures formed in fluidized beds can be investigated simultaneously without disturbing the flow field. After careful preparations, the technique is applied to a two-dimensional gas-fluidized bed under a spouting condition and the motion and the temperature of individual particles influenced by the bubble occurrence are clearly observed.

Keywords: 2-D Fluidized bed, heat transfer, infrared thermography, particle tracking velocimetry, particle tracking, convection motion

1. Introduction

Fluidized beds are widely used in industrial processes concerned with heat transfer such as combustion, gasification, catalytic reaction and calcination. The heat transfer in fluidized beds is governed by several mechanisms. Solid particles in the beds are fluidized by injected gas flow and the gas goes through the small gaps between particles. When a temperature difference exists between gas and solid phases, the convective heat transfer appears. During a fluidization, dense particles have contacts with surrounding particles, walls and immersed objects such as a heat exchanger pipe. The conductive heat transfer occurs due to the direct contacts between solids. In applications of which operating temperature is high, the radiative heat transfer becomes also important. In actual fluidized bed systems, these elemental heat transfers do not work independently and its behavior is quite complex.

Due to its complexity and measurement difficul-

ties, a numerical simulation model, which predicts the heat transfer phenomena in fluidized beds, has been desired. For the numerical analysis of fluidized beds, Lagrangian-Eulerian models are widely used (e.g., Tsuji et al., 1993; Hoomans et al., 1996 and Xu & Yu, 1997) and the models including heat transfers by several mechanisms are proposed as its extensions (Kaneko et al., 1999; Zhou et al., 2004a, 2004b; Sakurai et al., 2007; Zhao et al., 2009 and Zhou et al., 2009, 2010). Complex interactions between particles, gas flows and walls induce the formation of characteristic spontaneous flow structures such as bubbles in beds. Bubbles are far larger than the particle and have a larger rising velocity. Upward convective motion of particles is induced by the bubbles and the circulation and mixing of the particles are well enhanced in the beds accordingly. Each particle has finite volume and finite heat capacity and they can bring heat by its convective motions. The particle convection does not directly contribute to the heat exchange between two phases, however, as a result of convective motion, particles have contacts with other particles and gas flows that have different temperatures and exchanges heat. The heat transfer in fluidized beds cannot be discussed without the convective motion of individual particles induced by the characteristic spontaneous flow structures.

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¹ 2-1 Yamada-oka Suita, Osaka 565-0871

* Corresponding author

TEL & FAX: 81 6 6879 7317

E-mail : tak@mech.eng.osaka-u.ac.jp

The characteristics of spontaneous flow structures have been one of main topics in the fluidized bed researches (e.g., Kunii & Levenspiel, 1991; Jackson, 2000). It is not our purpose to review all the results in this paper while a large number of theoretical and experimental studies exist. Comparing to that, studies that treat the convective motion of individual particles induced by spontaneous flow structures are relatively limited. Lin et al. (1985) investigated the motion of a particle in a fluidized bed by using a particle tracking facility they developed. A radioactive particle made of ^{46}Sc is used as a tracer. Particle tracking is performed by measuring gamma rays emitted from the tracer particle by using twelve photomultiplier detector tubes. Mostoufi & Chaouki (2001) also performed a particle tracking by using a ^{198}Au radioactive tracer particle. They investigated the diffusivity of particles to know the local mixing characteristics in a fluidized bed. Stein et al. (2000) measured a particle motion in three-dimensional gas fluidized bed by using positron emission particle tracking (PEPT) technique. In the study, a resin particle activated by the ion exchange with irradiated water was used as a tracer. A particle's trajectory in a bubbling fluidized bed was obtained for each run. It is also possible to obtain averaged flow fields by continuing these Lagrangian measurements for a long period. By using PEPT measurement technique, Hoomans et al. (2001) obtained a time-averaged particle velocity distribution for a two-dimensional bubbling gas-fluidized bed and Link et al. (2008) obtained RMS particle velocity distributions in addition to time-averages for a spout-fluid bed. In these measurements, the position of tracer particle cannot be determined in prior to the measurement and the accuracy of measurement depends on the probability of the tracer particle's occurrence at each position. These tracking techniques are non-invasive and provide important data for three-dimensional motion of individual particles. It greatly helps the understanding of convective and mixing motion of particles in the beds. However, by these techniques, it is difficult to track a large number of particles at once. The measurement by using these techniques is still insufficient to investigate the relation between the convective motion of individual particles and the characteristic flow structures such as bubbles of which behaviors are unstable and changing at every moment.

For the heat transfer characteristics of fluidized beds, large numbers of studies have been performed from the applicational point of view. The purpose of these studies is to obtain the heat transfer coefficient,

h , of the whole bed and do not go into the detail of relations between heat transfer and flow structures formed inside of the beds (Kunii & Levenspiel, 1991). Studies that measure temperature distributions formed in beds also exist. In these studies, temperature distributions were obtained by inserting the single-point probe such as a thermocouple into a certain position of beds. During a measurement, inserted probes are expected to have convective heat transfers with surrounding gas flows and conductive heat transfers with solids under contact. It is difficult to know the temperature of individual particles by these technique and the studies concerned with the temperature of particles under a fluidization do not exist as much as we know.

For the better understandings of heat transfers in fluidized beds and further improvement of numerical models, it is important to know the relations between spontaneous flow structures, convective motions of individual particles and heat transfers. In the present study, a simultaneous measurement technique based on the coupling between particle tracking velocimetry (PTV) and infrared thermography (IT) measurement is presented. By using the technique, the motion and the temperature of individual particles can be directly observed and its relations with the flow structures formed in beds are investigated without disturbing the flow field.

In section 2, the measurement technique is presented. In section 3 and 4, the technique is applied to a two-dimensional Labo-scale fluidized bed under a spouting condition. In section 5, conclusions of the paper are shown.

2. Measurement Techniques

2. 1 Particle tracking velocimetry (PTV)

PTV is a measurement technique of particle velocity based on the analysis of video images. In principle, the velocity of a particle, $u_p = \Delta x / \Delta t$, is obtained by measuring the displacement of the particle Δx from two sequential images that have an interval Δt . PTV is developed mainly in the field of fluid velocity measurement in which tracer particles that have an enough response to a local flow change are tracked. A number of algorithms have been developed to find a particle uniquely from sequential images. In fluidized bed, particles have contacts with other particles and walls very frequently and the direction and the magnitude of particle velocity can change drastically. The majority of PTV algorithms based on the high autocorrelation of tracer particles are not for the measurement in fluidized bed. In the present

study, nearest-neighbor method is utilized. In the nearest-neighbor method, the frame rate of camera is adjusted to make the displacement of particle in two sequential images should be less than the particle radius. By enforcing this constraint, a perfect matching of particle image is possible even if a sudden change of particle velocity takes place.

2. 2 Procedure of PTV based on nearest-neighbor method

In this section, the procedure to obtain a particle velocity distribution based on the nearest-neighbor method is shown. We postulate the usage of digital video camera in the following explanation. It is also assumed that the size of pixel is sufficiently small comparing to the size of particle in images.

Due to the device characteristics of camera mainly, noises that can be a source of unphysical velocity vectors are included in original movie images in actual measurements. As the first step, Laplacian and smoothing filters (The Visualization Society of Japan (ed.), 2002) are applied to original images to diminish these noises. In the present PTV measurement, the position of particles at a certain time step is determined by estimating a correlation function between an image at the time step and a standard particle image. As the second step, a particle is chosen from a series of video images and its brightness distribution is stored as a standard particle image. We pay attention to the lighting, however, it is difficult to achieve the uniformity and the brightness distribution of particle image can vary depending on its location in actual. In the present study, three particles existing in different positions are chosen as standard particle images. As the third step, the distributions of correlation function between a video image and the standard particle images are obtained. The fourth step is to find the central coordinate of each particle. The pixels that show the highest correlation is expected to include the center of particles. At this step, a correlation function distribution is not separated for each particle. To find the center pixel of each particle, sub-areas that include one center pixel and surrounding pixels are extracted from a correlation function distribution. In the present study, the extraction is performed by using a threshold method. A group of continuous pixels of which correlation function is larger than 0.85 and is expected to include the particle center and extracted as a sub-area. By searching the pixel, which has the peak value in each pixel sub-area, the center coordinate of each particle is obtained in the pixel-level accuracy. In this study,

sub-pixel analysis (The Visualization Society of Japan (ed.), 2002) is also performed and the coordinate of the particle in sub-pixel level accuracy is obtained. In the nearest-neighbor method, the particles having the closest coordinates in two sequential images are the same one because the displacement is restricted to be less than the particle radius. The velocity of a particle is obtained by estimating the displacement Δx in the interval Δt , the temporal-development of particle velocity distribution is obtained by repeating the operation for all sequential images. As we discussed in section 4, it is also possible to obtain the trajectory of particles by using the PTV. The present measurement is purely two-dimensional and only particles of which coordinate is detectable from images are the object of measurement. The tracking of particles is terminated when the overlap of particle images occurs due to its in-depth motions while it is recommenced whenever the detection of particle coordinate can be performed again.

The accuracy of particle displacement measurement is most influential for the overall accuracy of present PTV measurement. The accuracy of displacement measurement of the present measurement system was examined in previous study (Oh et al., 2010). Pre-defined particle displacements were measured by the present PTV along with a CCD laser displacement sensor (LK-G35, Keyence Corporation). From the examination study using a particle with 3.14 mm diameter, we confirmed that the RMS error fraction becomes 100 % at 0.02 mm and 1.27 % at 1.57 mm which corresponds to the particle radius and the maximum displacement allowed in the nearest-neighbor method, respectively.

2.3 Temperature measurement by infrared thermography (IT)

Particle temperature is measured by infrared thermography (IT) technique. An IT camera can detect infrared rays emitted from the surface of objects such as a solid particle. The energy of infrared ray is theoretically related to the temperature of the object surface as

$$W = e \sigma T^4 \quad (1)$$

where W is the infrared energy, e is the emissivity, T is the surface temperature and $\sigma (= 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)$ is the Stefan-Boltzmann constant. The emissivity is specific to the material of object and we can estimate the temperature of object by measuring the infrared energy.

If the surface of object is polished, infrared rays from surroundings are reflected on the surface of object and it will lead misinterpretations of temperature. This is also true in-between particles. The infrared rays emitted from particles have reflections on the surface of neighboring particles. This results in multiple reflections of infrared rays on all particles' surface and make the quantitative evaluation of particle temperature difficult (Sakurai et al., 2007). In this study, to reduce the reflection effect on particle surface, all particles are coated with black body paint (THI-1B, TASCO JAPAN) as shown in **Fig. 1**. The catalog value of ϵ for the black body material we introduced is 0.94. From a preliminary study, however, we confirmed that the emissivity varies depending on the temperature as shown in **Fig. 2**. Both PTV and IT are optical measurement techniques and only optically accessible particles are the object of measurement. To enable the observation of particle

motion in a fluidized bed, an observation window of container should be made of transparent materials such as glass and acrylic resin. In case of the IT measurement, a special attention should be paid because transmission characteristics of infrared rays change depending on material. In the study, spinel glass (MgAl_2O_4) which exhibits good transmission characteristics in the visible light, the near-infrared and the mid-infrared wavelength ranges is utilized for the observation window. The transmission rate of spinel is far better than the other materials while it is not perfect and the decay of infrared energy still exists. Along with the correction for the temperature-dependency of emissivity, the results of temperature measurement appear in this paper are corrected using the following equation.

$$T = 1.0466T_{\epsilon=0.94} + 8.0873 \quad (2)$$

(a) Uncoated Aluminium particle

(b) Coated Aluminium particle

Fig. 1 Coating of particle by black body paint.

Fig. 2 Temperature dependency of emissivity.

where $T_{e=0.94}$ is the temperature measured by the IT camera introduced in section 3 and T is the corrected temperature. This correction equation is obtained by comparing the results of IT measurement performed through a spinel by keeping $e = 0.94$ and that by a thermocouple.

3. Experimental Setup

The present measurement technique is applied to a Labo-scale fluidized bed under a spouting condition. The experimental setup is shown in **Fig. 3**. This is a specially designed apparatus for the measurement of fluidized bed with heat transfer. The vessel has 400 mm height, 76 mm wide and 21 mm depth. This is a two-dimensional fluidized bed because the depth of the bed is restricted comparing to other dimensions. A slit nozzle with a cross-section 11 mm $\times$ 21 mm is installed at the bottom center of the vessel as shown in **Fig. 4**. The observation window is made of spinel. An air flow at 292 K generated by a compressor is injected from the slit nozzle. The flow rate is controlled by the regular and measured by using the laminar flow meter (LEF50-B, Tsukasa Sokken Co., Ltd.). Spherical Aluminium particles with the average diameter of 2.0 mm (Amatsuji steel ball MFG Co., Ltd.) are used. The measurement of temperature distributions existing inside of particles under fluidization is challenging and beyond of our study. It is known that the temperature of a particle is almost uniform if the size of particle is small or the thermal conductivity of the particle is large enough. Biot number, $Bi = hd_p/k_p$, is an index of this assumption where h is the heat transfer coefficient, d_p the particle diameter

and k_p the thermal conductivity of the particle. In case of the Aluminium particles we used in the study, $Bi < 0.1$ and the assumption is almost valid. After the coating, particle's average diameter becomes 2.1 mm. Due to the existence of coating layer on the particle's surface, the delay of heat transfer was concerned. In our preliminary study, we confirmed that the effect of coating layer is almost negligible in the present condition. In prior to the measurement, the particles are heated up by using an electric oven (DX400, Yamato Scientific Co., Ltd.). After keeping its temperature to 423 K for 20 min in the oven, the particles are installed into the vessel. Measurements are started as soon as the installation of particles is finished because the particles loose heat due to the temperature difference with the vessel walls and the atmosphere. To perform measurements in a fluidized state, superficial velocity is set to $u_f = 1.50$ m/s while the minimum fluidization velocity, u_{mf} , is 1.09 m/s in the present condition. The initial bed height is set to 55 mm. The effect of radiative heat transfer is small and negligible in the present condition.

Both IT and PTV are measurement techniques based on the analysis of video images and it is preferred to obtain particle motion and its temperature from a series of video images acquired by a single camera. It is not possible to detect infrared rays using a conventional high-speed camera and it is required to perform PTV for IT video images in the present case. As we discussed in section 2.1 and 2.2, however, the constraint exists on the frame rate of video recording in the case of nearest-neighbor method. In this study, two cameras are used simulta-

Fig. 3 Experimental setup.

Fig. 4 Spouting condition.

neously because the temporal resolution of currently available IT cameras is not sufficient for the PTV based on the nearest-neighbor method. A high-speed video camera (FASTCAM ultima1024, Photron, Ltd.) is used for the velocity and trajectory measurements by PTV and an infrared thermography video camera (TVS-8502, NEC Avio Infrared Technologies Co., Ltd.) is for the temperature measurement. Specifications of cameras are shown in **Table 1**. In the measurement, the frame rate of high-speed camera is set to 500 fps to meet the condition of the nearest-neighbor method in the present condition. For the IT camera, it is set to 120 fps, which is the highest frame rate of the camera. In the present setting, the resolutions of high-speed and IT cameras are 0.153 and 0.332 mm/pixel, respectively. The ratios between particle diameter and pixel size in video images, $d_p/\Delta_{\text{pixel}}$, become 13.73 in case of the high-speed camera and 6.33 in case of the IT camera.

To avoid the physical interference between two cameras, measurements are performed from different angles as shown in **Fig. 3**. The IT camera is installed in front of the bed as its optical axis is perpendicular to the front wall of the bed. The high-speed camera is installed in an upper position of the IT camera. The angle between its optical axis and the bed wall is $5/12\pi$ rad. Measurements are performed for 8.1 sec after fluidization is started.

4. Results and Discussion

Fig. 5 (a), (b) show the temporal developments of particle motion and temperature just after the flu-

idization is started ($t - t_0 = 0.05$ to 0.40 sec) and after several seconds is passed (5.95 to 6.30 sec), respectively. t shows the time and t_0 the time when the measurement is started. In the figures, particle velocity distributions obtained by PTV are superimposed on IT images. A typical flow pattern under a spouting condition is observed in **Fig. 5 (a), (b)**. The formation of bubble in the region above the nozzle inlet is clearly confirmed at 0.15 and 0.20 sec in **Fig. 5 (a)** and at 6.05 and 6.10 sec in **Fig. 5 (b)**. During the fluidization, the particle layer is divided into fluidized and unfluidized regions as schematically shown in **Fig. 6**. The motion of particles is active in the fluidized region. Bubbles go through the particle layer intermittently and the particles existing in the region above the nozzle inlet are convected upward (0.15 sec in **Fig. 5 (a)** and 6.05 sec in **Fig. 5 (b)**). After reaching the region near the free surface of particle layer, their behaviors turn to lateral and downward motions (0.20 sec in **Fig. 5 (a)** and 6.10 sec in **Fig. 5 (b)**). The process is repeated and the intermittent circulation of particle flow is formed in the fluidized region. In contrast, the motion of particles is small in the unfluidized regions existing near lower corners.

We can recognize the temperature of individual particles from **Fig. 5 (a), (b)**. As soon as the particles are installed, conductive heat transfers with container walls are started and the temperature of particles contacting with the front wall decreases to 363–373 K when the observation is started. The decrease of temperature is more apparent for the particles contacting with both front and side walls, it becomes

Table 1 Specifications of cameras

camera	high-speed camera (FASTCAM ultima1024, Photron, Ltd.)
maximum frame rate	1000 fps
maximum pixels	1024 × 1024
lens	NIKKOR 50 mm, $f=1.2$ (Nikon Corp.)
camera	infrared thermography camera (TVS-8502, NEC Avio Infrared Technologies Co., Ltd.)
detector	InSb focal plane array
measurable temperature range	233–1173 K
resolution	less than 0.025 K
accuracy of measurement	± 2 K or $\pm 2\%$ of reading, whichever is greater
detectable wave length range	3.5–4.1, 4.5–5.1 μm
maximum frame rate	120 fps
thermal image pixels	256 × 236
lens	standard lens, 30 mm

Fig. 5 (a) Temporal development of particle motion and temperature.

under 360 K as observed at 0.05 sec in **Fig. 5 (a)**. In the region just above the gas inlet, the relative velocity and relative temperature between gas and particles should be large because a cold air flow is injected into the bed consisted from hot particles. From the point of view of convective heat transfer, the temperature of particles in the fluidized region should be decreased faster comparing to that in the unfluidized region. **Fig. 5 (a), (b)** give contradicted expressions

for us, that is the particle temperature seems higher in the fluidized region and lower in the unfluidized region. The similar tendency is also confirmed in the measurement for a long period shown in **Fig. 7**. It is noted that this is the result from $t-t_0=0.05$ to 7.05 sec and the motion of each bubble is not captured because it is depicted every 1.00 sec while it is 0.05 sec in **Fig. 5**. From **Fig. 7**, we can confirm the decrease of overall temperature in the bed while the particle

(b) $t-t_0=5.95-6.30$ sec

Fig. 5 (b) Temporal development of particle motion and temperature (continued).

temperature seems relatively higher in the fluidized region. We expect this is due to the in-depth motion of particles. The depth of the bed is 21 mm, which is equivalent to $10 d_p$ of the coated particle, and three-dimensional motions and arrangements of particles are allowed. Before the fluidization, the particles existing internally do not have direct contacts with the container walls and the decreasing of temperature is relatively small. In the fluidized region, the motion

of particles is active due to the bubble occurrence and the three-dimensional motion of particles is enhanced. As a result of that, the particles existing in the internal region and keeping higher temperature come out to the front. Comparing to that, the motion of particles existing in the unfluidized region are very small and the particles that keep touching with front and side walls lose more heat.

Fig. 8 shows typical results of particle tracking

Fig. 6 Fluidized and unfluidized regions. The image is obtained at $t - t_0 = 6.9$ sec.

Fig. 7 Temporal development of particle motion and temperature for a long period ($t - t_0 = 0.05$ to 7.05 sec).

Fig. 8 Trajectories of particles. All tracking are started at $t - t_0 = 3.85$ sec. Filled large symbols show the starting points of tracking. Open symbols show the position of particles at every 0.01 sec after the tracking is started.

Fig. 9 Trajectory of particle 1 appeared in **Fig. 8** and its relations with characteristic flow structures ($t - t_0 = 4.45$ to 4.92 sec).

by the PTV, it is possible to track large numbers of particles at the same time. All trajectories shown in **Fig. 8** are from $t - t_0 = 3.85$ sec. This is a purely two-dimensional measurement and the tracking is terminated when the coordinate of a particle is not detectable due to the overlap of particle images and the length of tracking differs depending on the particles in **Fig. 8**. In the figure, the filled large symbols show the starting positions of tracking and the open symbols show its locations at every 0.01 sec. From **Fig. 8**, we can confirm that the motion of particles differs depending on its initial positions. In general, the particles existing in the regions slightly deviated from the bed center (particle 1, 4, 5 and 6) have circulation patterns. The motion of particles is not steady and the acceleration and the deceleration of particle are repeated. In the PTV measurement, it is also possible to investigate the relation between the motion of individual particles and the flow structure changing at every moment. **Fig. 9** shows the results of particle tracking along with particle images obtained by the high-speed camera. Only results of particle 1 from $t - t_0 = 4.45$ to 4.92 sec are shown here. The particle is convected upward along with a bubble occurrence at $t - t_0 = 4.51$ and 4.62 sec. The particle's movement becomes smaller and tends to deposit in the layer at $t - t_0 = 4.68$ sec while it is reactivated again by the occurrence of next bubble ($t - t_0 = 4.74$ to 4.86 sec). The process is repeated and we obtained the trajectories shown in **Fig. 8** as a result.

5. Conclusions

A simultaneous measurement technique based on the coupling between particle tracking velocimetry (PTV) and infrared thermography (IT) measurement was presented in the paper. By using the technique, it is possible to obtain the motion and the temperature of particles in fluidized beds. After the careful preparations, the technique was applied to a Labo-scale two-dimensional fluidized bed under a spouting condition and the following conclusions are obtained:

(1) The motion of particle is obtained by PTV based on the correlation of particle images. By using the nearest-neighbor method, it is possible to measure the velocity of particles that have contacts with surrounding particles and walls frequently in fluidized beds. Unlike the techniques such as particle image velocimetry (PIV), the measurement is performed in the particle-level and the motion of individual particles induced by the characteristic flow structure such as bubbles is observable.

- (2) It is possible to track a number of particles at once and know the relations between Lagrangian particle motions and flow field at each instance.
- (3) Temperature measurement of particles based on the infrared thermography technique is beneficial, however, it is required to pay close attention to its calibration for quantitative measurements.
- (4) The combined method between PTV and IT is a unique measurement technique which provides the motion and the temperature of individual particles in fluidized beds simultaneously. It is powerful to have deeper understandings on the heat transfers in fluidized beds.
- (5) The flow field is clearly divided into fluidized and unfluidized regions in a two-dimensional fluidized bed under a spouting condition. The motion of particles in the fluidized region is largely influenced by the behavior of bubbles. The temperature of particles in the fluidized region seems relatively higher comparing to that in the unfluidized region due to the three-dimensional active motion of particles in the fluidized region.

For heat transfer problems in fluidized beds, further quantitative studies using the technique developed in the present study will be performed.

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Author's short biography

Takuya Tsuji

Dr. Takuya Tsuji is an associate professor of Mechanical Engineering, Osaka University. He obtained his Ph.D. in Energy Engineering from Kyushu University, Japan and joined the group of Prof. Toshitsugu Tanaka in Osaka University in 2004. From 2009, he is also occupying a position in an industry-academia collaboration laboratory funded by Komatsu Ltd. His research focuses on the dynamics of particle-laden flows and granular flows and he is engaged in numerical modeling / simulation and experimental studies at several different scales.

Takuya Miyauchi

Mr. Takuya Miyauchi graduated from Osaka University in 2010 and now he is a graduate student in Department of Mechanical Engineering, Graduate School of Engineering, Osaka University. He studies particle behaviors in two-dimensional fluidized bed by using Particle Tracking Velocimetry (PTV) technique and Infrared Thermography technique.

Satoshi Oh

Mr. Satoshi Oh graduated from Osaka University in 2009 and now he is a graduate student in Department of Mechanical Engineering, Graduate School of Engineering, Osaka University. He studies particle behaviors in two-dimensional fluidized bed by using Particle Tracking Velocimetry (PTV) technique.

Toshitsugu Tanaka

Dr. Toshitsugu Tanaka graduated from Osaka University in 1982, and from the graduate school of Osaka University in 1984. He received the Ph.D. degree of Engineering from Osaka University in 1994. He became a Research Associate at Osaka University in 1984 and an Associate Professor at Osaka University in 1996. Currently, he is a Professor in the Department of Mechanical Engineering of Osaka University since 2003.