Quantitative flow visualization of fluidized-bed under normal- and down-flow-mode operations by neutron radiography

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Abstract  Heat transfer characteristics of tube-banks immersed in a fluidized-bed is dominated by the time-averaged as well as statistical characteristics of bed-material movement, especially, in the neighboring region of heat transfer tube. The neutron radiography and image processing technique have been successfully applied to the visualization of flow field and quantitative measurement of void fraction in the bed. This quantitative visualization technique is verified as a useful means in understanding the flow behavior and thus the heat transfer mechanisms.

Introduction

Recent local and global environmental difficulties bring about further demand of protection or control of emissions, such as NOx, SOx and more severely dioxin. On the other hand, energy problem is still quite important for further development of human welfare that, in some case, results in a trade-off with the environmental problem. One promising technique to break through this trade-off relationship is fluidized-bed combustion for coal and/or incineration firing, owing to the in-furnace/in-bed processing and controllability of the furnace temperature to reduce emissions. Fluidized-bed combustion or reaction is also a useful technology in recently developed integrated coal gasification combined cycle (IGCC). In designing such a fluidized-bed combustion/reaction system, it is essential to have a suitable similarity law of the fluidized-bed. Suitable constitutive relationships of heat transfer are, of course, of prime importance in a numerical simulation that will be used in the design stage.

Numerical simulations of such multiphase flow system are conducted based on, mainly, diffusion (or mixture) model and two-fluid model. Recent advanced computational technologies have made it possible, using two-fluid model, to obtain gas and solid velocities, void fraction distribution, pressure distribution, and moreover the time-dependent behavior of gas bubbles formed in the bed. One of the examples can be found in the works by Gidaspow et al. (1983a, b). They measured the void fraction distribution in two-dimensional fluidized bed by use of a γ-ray densitometer, and their two-fluid model was examined through the comparison with experimental results of the void fraction and the growing process of gas bubble. Another interesting example is the paper by Kuipers et al. (1993) who simulated gas bubble in a two-dimensional bed based on two-fluid model. It is needless to say that such a two-fluid modeling consists of six field equations of mass, momentum and energy, and closure laws such as topological, constitutive and transfer laws, as has been mentioned by Enwald et al. (1996). They also presented an extensive review on two-fluid modeling that are useful for understanding the state of art in two-fluid modeling. To obtain such closure laws and also to verify such simulations, it is still essential to measure or obtain quantitative information of various parameters, including void fraction; particle or gas-bubble velocities and heat transfer coefficient, as well as qualitative information about the flow pattern in the fluidized bed.

Heat transfer characteristics, shown in Fig. 1 as an example, of tube banks immersed in the fluidized bed is one of the essential constitutive relationships, because the bed temperature control is a key technology for the protection of emissions. Heat transfer characteristics on tube surface in a fluidized-bed have been widely investigated so far (e.g. Xavier and Davidson 1985; Baskakov 1985; Molerus and Wirth 1997). The principal heat transfer mechanism has been classified into three categories, i.e. solid convection, gas convection and radiation (Saxena et al. 1978; Horio 1987), depending on the particle size and the temperature difference between the tubes and bed materials. Among such principal mechanisms, the solid convection has a practical importance in the heat exchanger design of fluidized-bed boiler with bed materials of 100–400 μm diameters (Martin 1984a, b; Saxena et al. 1978; Saxena 1989; Ozawa et al. 1998a, b). Recent experimental works by Kuroaki et al. (1995) and Miyamoto et al. (1995, 1996)
focused on an interesting feature of solid particle behavior on and close to the heat transfer surface on the basis of fiber-probe measurement. However, with reference to the heat capacities of the tube wall and each particle, it may be stated that the heat transfer is controlled not by each particle movement but by a group of particle. In this sense, the representative length scale is an order of, at least, the thickness of thermal boundary layer including gas and solid around the tube. In other words, the behavior of certain mass of solids or emulsion of solids and gas, i.e. the flow pattern, plays an important role in the convective heat transfer around tubes (e.g. Lee and Kern 1972; Staub 1979; Chandran and Chen 1982; Sitnai and Whitehead 1985; Konrad and Huang 1987). Then the void fraction behavior becomes a representative quantity to be measured in experiments, and also is one of the essential parameters in constructing a certain type of continuous flow modeling, such as the two-fluid model.

To measure the void fraction, various approaches have been conducted so far. These approaches are classified roughly into three categories, i.e. light attenuation method, probe method and radiography. The first method is only available in a rather thin bed, and the second may cause a certain disturbance in the flow field (Rowe et al. 1981), if relatively large probe is inserted into the bed to measure the space-averaged void fraction. The radiography techniques by use of X- and γ-rays have been so far applied to fluidized beds. The examples of X-ray radiography can be found in the works by Rowe et al. (1971, 1979 and 1981) and Barreto et al. (1983). The γ-ray has been used, for example, by Gidaspow et al. (1983a), as mentioned above. They used glass balls, quartz sands, coal powder or alumina powder as the bed materials, while the bed materials must be selected taking the mass attenuation coefficient as described below into consideration to obtain high-contrast images. Such problem may be rather serious when segregation phenomena that is not the present case is the target of investigation. In such a case, large particles but almost the same density as the bed materials must be visualized with high contrast against the bed materials, while it is rather difficult to find out such particle system in both cases of X- or γ-rays. In case of neutron radiography, on the other hand, such a problem can be easily overcome by coating particles with high-attenuation materials as in the present case so as to have high-contrast images. Thus, the neutron radiography show high flexibility in selecting the bed and setup materials owing to the attenuation characteristics being different from those of X- and γ-rays, although a neutron source such as accelerator and nuclear reactor is needed (Takenaka et al. 1990).

In this series of investigation, quantitative flow visualization was conducted to obtain clear understanding of the flow pattern and void fraction behavior, using a neutron radiography (NRG) technique and image processing. Only a few researchers such as Catchen et al. (1987) and Takenaka et al. (1990) conducted an application of neutron radiography technique to fluidized-beds, while the quantitative measurement of void fraction including its fluctuation behavior has been hardly reported except the first trials by Ozawa et al. (1996b and 1998a, b) so far. This paper presents detailed description of the flow visualization by NRG and image processing with a short discussion of the accuracy of measurement. Then, quantitative void fraction behavior and thus the flow pattern are discussed on the cross-flow tube banks in a normal fluidization and down-flow of bed materials. Here, the normal fluidization means the conventional bubbling bed aerated from the bottom and the circulation of bed materials is limited in the bed. Thus the time-averaged solid flow rate through the whole bed is essentially zero. On the other hand, the down-flow mode means that the time-averaged movement of bed materials is directed downward through the bed being aerated so as to keep fluidization. Then the bed materials are circulated by means of an external lift channel from the bottom to the top of the bed. Such a down-flow mode of operation can be found in an external fluidized-bed heat exchanger of circulating fluidized-bed boiler. These two modes are schematically indicated by solid (normal mode) and dashed lines (down-flow mode), respectively, in Fig. 5c appeared below.

**Neutron radiography**

Neutron radiography is one of non-destructive inspection methods, and is quite similar to X-ray radiography. Such radiography is based on a difference in the attenuation rate of radio rays depending on the materials of the object. The mass attenuation coefficients of thermal neutrons and X-rays are well demonstrated in Fig. 2 (Takenaka et al. 1990). The solid line represents the mass attenuation coefficients for X-ray, and other plots for neutrons. The mass attenuation coefficient for X-ray is a function of atomic number, and that of neutrons, on the other hand, depends on each element. For example, hydrogen, cadmium, gadolinium and boron highly attenuate neutrons, but aluminum, iron, chrome and nickel only slightly attenuate. Thus the former group is opaque against neutron, and the latter group is almost transparent against neutron rays. Such attenuation characteristics make it possible to visualize, for example, high pressure boiling water in a stainless-steel tube (Takenaka et al. 1990). The present bed material is silica-sand (99.7 SiO₂) that is a general one in actual fluidized-bed combustors in the market. Then the bed material is almost transparent against neutrons even