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Study on the particle distribution of a horizontal multi-tube circulating fluidized bed

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ABSTRACT

A horizontal multi-tube circulating fluidized bed is designed and built to study the particle distribution in the horizontal tube bundle. The effects of the operating parameters, such as circulation flow rate, amount of added solid particles, diameter and density of particles on the fluidization and distribution of solid particles in the horizontal tube bundle are systematically investigated by using the image measurement and acquisition system of a charge-coupled device (CCD). Experimental results show that the particle distribution in the horizontal tube bundle is non-uniform. The solid holdup of particle is higher near the bottom of the tube bundle and lower near the top. The non-uniform degree decreases with the increasing of the circulation flow rate and the amount of added solid particles. The particles with smaller diameter and density are fluidized better and well distributed in the horizontal tube bundle and in a single tube. The phase diagrams are established to show the variation ranges of the operating parameters for more uniform particle distribution and relatively high solid holdup in the tube. High turbulent extent of water flow results in more uniform particle distribution in the horizontal tube. The results may be used to further solve the particle distribution problems in the horizontal tube bundle.

1. Introduction

Fouling or scaling on the heat exchanger surface is a major problem increasing both thermal resistance and pressure drop, thus affecting the initial capital investment as well as operating costs [1,2]. It is found that the layer formed by deposition of the solids on the tubes in a waste heat boiler can reduce the overall heat transfer coefficient by about 25% [3]. Liquid–solid circulating fluidized bed heat transfer technology is a promising online self-cleaning and heat transfer enhancing technology, which has been successfully applied in heat exchangers with the advantages of low investment and maintenance costs compared to other methods such as rotating scrapers [4–6]. It is reported that the boiling heat transfer is enhanced due to the presence of the solid particles, and the boiling heat transfer coefficient of the vapor–liquid–solid three-phase fluidized bed is about twice that of the vapor–liquid two-phase flow [7]. The fluidized solid particles can destroy the boundary layer of flow and heat transfer and increase the nucleus of boiling and the shear force to the wall. Deposit removal from heat exchanger walls and the enhancement of heat transfer are attributed to particle collisions with the wall [8].

As the key influence factor on the particle collisions with the wall, uniform particle distribution in heat exchanger tube bundle is the foundation and prerequisite as to achieve safe and effective operation. Qi et al. [9] adopted the Eulerian multiphase fluid model to simulate the particle distribution in a fluidized bed heat exchanger incorporating tube bundle arranged in parallel, showing good agreement with experimental measurements. Selma et al. [10] carried out an experimental and numerical investigation for the phase distribution and pressure drop in two-phase offset strip fin type compact heat exchanger.

The earlier researches, both numerical and experimental, focused on flow characteristics and hydrodynamics of the vertical liquid–solid circulating fluidized bed. Zheng et al. [11] conducted experiments to examine the radial distribution of solids holdup under wide range of operating conditions and to test the effect of particle density on the flow structure. The hydrodynamic characteristics in the bottom region of circulating fluidized bed risers with fluid catalytic cracking particles were studied by Zhu et al. [12] over a wide range of operating conditions. The results showed the radial solids concentration and corresponding radial profiles of standard deviation, particle velocity profiles, and probability density distributions. The effects of particles properties on the solid holdup in the riser of a liquid–solid circulating fluidized bed were investigated experimentally by Sang et al. [13]. Shilapuram et al. [14] experimentally investigated the effect of the location of the liquid distributor, method of operation, liquid viscosity, and solid inventory on the axial solid holdup distribution in the liquid–solid circulating fluidized bed. Dadashi et al. [15] developed an axisymmetric CFD model based on Eulerian–Eulerian approach incorporating the kinetic theory of granular flow to simulate the flow field in LSCFB riser. Wang et al. [16] simulated the flow behavior of solid phase by

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means of Eulerian–Eulerian in a liquid–solid fluidized bed with modified drag model based on energy-minimization multi-scale (EMMS) method. Liu et al. [17] proposed a cluster structure-dependent drag model to take the effect of clusters on momentum transfer between dispersed phase and clusters into account by means of an Eulerian–Eulerian two-fluid model. Predicted volume fraction and particle velocity distributions showed a good agreement with experiment data.

As the petrochemical industry and fluid transportation develop, the researches on the horizontal circulating fluidized bed have attracted wide attention [18]. Recently, a few experimental studies are directed towards the particle distribution in horizontal tube bundle. Liu et al. [19] studied the particle distribution of single pipe horizontal circulating fluidized bed with the spiral flow generator at different operating conditions. Qi et al. [20] used Eulerian multiphase model to simulate the flow of liquid–solid two phase in horizontal tube bundle heat exchanger and investigated the particle distribution and pressure drop in the heat exchanger. Numerical simulations of pneumatic conveying in pipes of circular cross-section based on an Euler–Lagrange approach were reported by Alletto et al. [21]. Barth et al. [22] conducted experiments to investigate deposition velocity of the particles in a horizontal turbulent duct flow by using optical microscopy and particle size spectrometry. Wang et al. [23] investigated heterogeneous ice slurry flow and concentration distribution in horizontal pipe with circular, rectangular and slit rectangular cross-section. However, the distribution of particles in the horizontal tubes has not been investigated comprehensively.

In this work, an experimental study is carried out in a cold model and transparent horizontal liquid–solid circulating fluidized bed heat exchanger using the advantages of visualization. The main aim of the research is to experimentally study the particle distribution in the horizontal tube bundle and single tube under different operating conditions. The CCD and the StreamPix data acquisition software are used to measure and record the fluidization and distribution of particles. This research can provide basic data for application of the fluidized bed heat exchangers with horizontal tube bundle in industry process.

2. Materials and methods

2.1. Experimental apparatus

The experimental setup is illustrated in Fig. 1.

A cold mold and transparent horizontal multi-tube circulating fluidized bed is designed to study the particle distribution in horizontal tube bundle. Basically it consists of the centrifugal pump, electromagnetic flowmeter, horizontal heat chamber, bottom horizontal single tube, data acquisition system and particle collection section.

The main part of the equipment is the horizontal heat chamber consisting of two shell covers and horizontal tube bundle which are all made of organic glass for the visualization study. The tube bundle arranged in the form of square arrangement consists of 17 tubes which have a diameter of 25 mm × 2.5 mm and a length of 1000 mm. The arrangement of tube bundle is shown in Fig. 2. The tube spacing is 1.5 times the outer diameter. The bottom horizontal single tube is also made of organic glass of 60 mm × 4 mm in diameter and 400 mm in length.

The CCD image measurement and data acquisition system consists of a CCD camera, a computer and the digital video recording software StreamPix, which is used to acquire the distribution and fluidization of the particles in the system. The image acquisition rate is 38 frames per second. In the experiment, the CCD camera is placed at four different locations. The three locations are on the horizontal heat chamber and another one on the bottom horizontal single tube. The flow conditions of the four sections are liquid–solid two-phase flow.

2.2. Experimental materials

The experimental working materials include water and the inert solid particles used as the liquid and solid phases, respectively. The types of inert solid particles and relevant properties are shown in Table 1.

2.3. Experimental parameters and measurement methods

In this experiment, the operating parameters include the types of the inert solid particles, the amount of added solid particles, and the circulation flow rate of the liquid–solid two-phase.

The amount of added solid particles ε is the ratio of the volume of the solid particles to the total volume of the liquid and solid two phases which is the volume of this circulating system measured at the beginning of the experiments by using tap water. In this experiment, ε is set to 0.5%, 1.0%, 1.5%, and 2.0%.

The circulation flow rate of the liquid–solid two-phase is measured by the electromagnetic flowmeter whose type is LDG-50, and the measuring range is 2–40 m^3/h and the precision grade is 0.5. The circulation flow rate in the experiment is set to 7.9, 9.9, 11.8, 13.7, 15.7, 17.7, and 19.9 m^3/h.

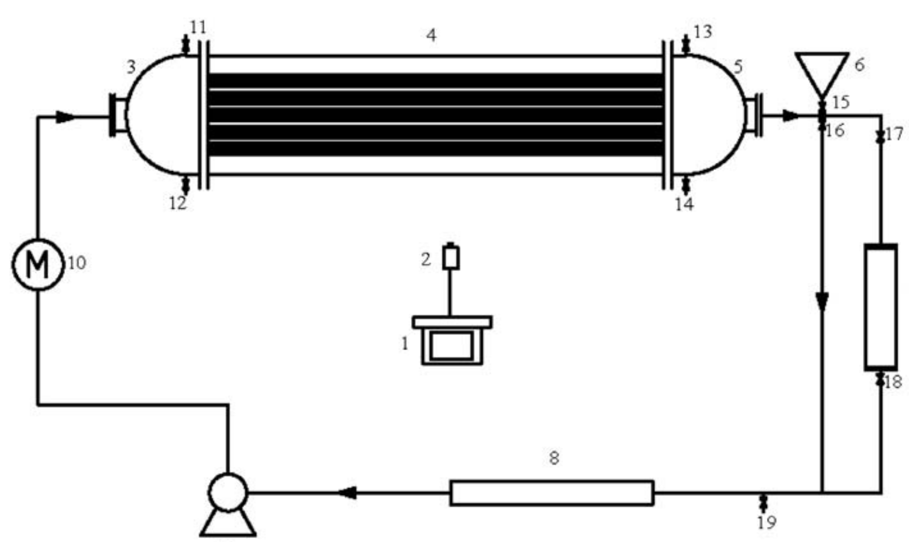

Fig. 1. Schematic diagram of the horizontal multi-tube circulating fluidized bed system. 1—computer; 2—CCD; 3—front shell cover; 4—horizontal tube bundle; 5—rear shell cover; 6—loading hopper; 7—particle collection section; 8—the horizontal singe tube; 9—centrifugal pump; 10—electromagnetic flowmeter; 11–19—ball valves.