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Effects of the ship motion on gas–solid flow and heat transfer in a circulating fluidized bed

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ABSTRACT

A series of experiments on a circulating fluidized bed (CFB) was performed to investigate the effects of ship motion on gas–solid flow and heat transfer in the CFB. Rolling period, rolling amplitude, inclination angle, superficial velocity, particle diameter range, and solid circulation flux were varied in the experiments. The following results were obtained: (1) When the CFB undergoes rolling motion, the downflow of particles changes periodically and the solid volume fraction increases at the riser bottom. As a result, the time-averaged total pressure drop of the CFB in rolling motion becomes larger than that at the upright attitude. Similarly, the total pressure drop of the CFB at an inclined attitude is larger than that at the upright attitude. (2) The total pressure drop of the CFB in rolling motion is hardly affected by rolling period. As rolling amplitude increases, on the other hand, the effects of rolling motion become more remarkable. From these results, it is concluded that gravity dominantly affects gas–solid flow in the system. (3) At an inclined attitude, the symmetry of the flow field with respect to the riser center plane breaks, and heat transfer at the lower wall of the riser is promoted. As inclination angle increases, heat transfer augmentation becomes more remarkable. Similarly, the heat transfer coefficient in rolling motion is larger than that at the upright attitude. (4) Heat transfer augmentation by ship motion is concluded to be caused by the direct contact between solid particles and the heater surface owing to the vertical component of gravity to the surface.

1. Introduction

The authors previously took notice of the CFB owing to its excellent reaction efficiency and heat transfer characteristics, and are now conducting a study to develop a compact and highly efficient marine waste heat recovery system [1,2]. In their proposed system, by using the CFB, sulfur in the exhaust gas is eliminated and waste heat is efficiently recovered. Because the system is installed in a ship, its performance may be affected by ship motion, i.e., rolling and inclination.

As for the effects of inclination on a bubbling fluidized bed, several studies have been reported [3–10]. O'dea et al. [3] carried out experiments on gas–solid fluidized beds inclined at angles between 0° and 45° to the vertical with four different types of powder. Flow regimes and a transition condition were identified in their experiments and verified using a theoretical model. Hudson et al. [4] investigated a liquid–solid fluidized bed inclined up to 10° from the vertical. They measured the local holdup and circulation pattern of the liquid and solid phases, and developed a simple model for obtaining the solid circulation pattern. Chaikittisilp et al. [5] performed a DEM simulation for particle motion in an inclined fluidized bed to investigate the mixing behavior of solid particles. Yakubov et al. [6] studied the dynamics and structure of an inclined liquid–solid fluidized bed experimentally over the entire range of inclination angles, and reported that the critical velocity for bed escape reaches its maximum at about 45° of inclination.

Concerning the effects of rolling motion on the bubbling fluidized bed, Yasui et al. [11] conducted experiments on a 2D fluidized bed mounted on rolling equipment. The rolling amplitudes in their experiments ranged from 0° to 20°, and the rolling periods were 10.6 s and 14.2 s. They classified the flow regimes of the bed into three types, and measured the heat transfer coefficient at the surface of horizontal tubes immersed in the bed. Nakanishi et al. [12] also performed cold model experiments to investigate the behavior of the bed and clarified the effects of inclination and rolling on the pressure drop distribution in the bed. Their rolling amplitudes ranged from 0° to 30° and the rolling frequency varied from 0.1 Hz to 0.6 Hz. Namie et al. [13] carried out combustion experiments on a fluidized bed boiler mounted on a rolling bed. The rolling amplitudes of their experiments were 10° and 20°, and rolling period was changed at three steps: 5, 10, and 20 s. They measured the temperature distribution of the bed and the boiler efficiency of the furnace.

Furthermore, Huilin et al. [14] simulated the dynamic behavior of gas–solid flow in a riser using a transient 2D hydrodynamic model based on the kinetic theory of granular flows, and reported that strong flow distortions, such as a shift in the maximum solid mass flux from the center to the first quarter of the pipe, are induced by an inclination of a few degrees.

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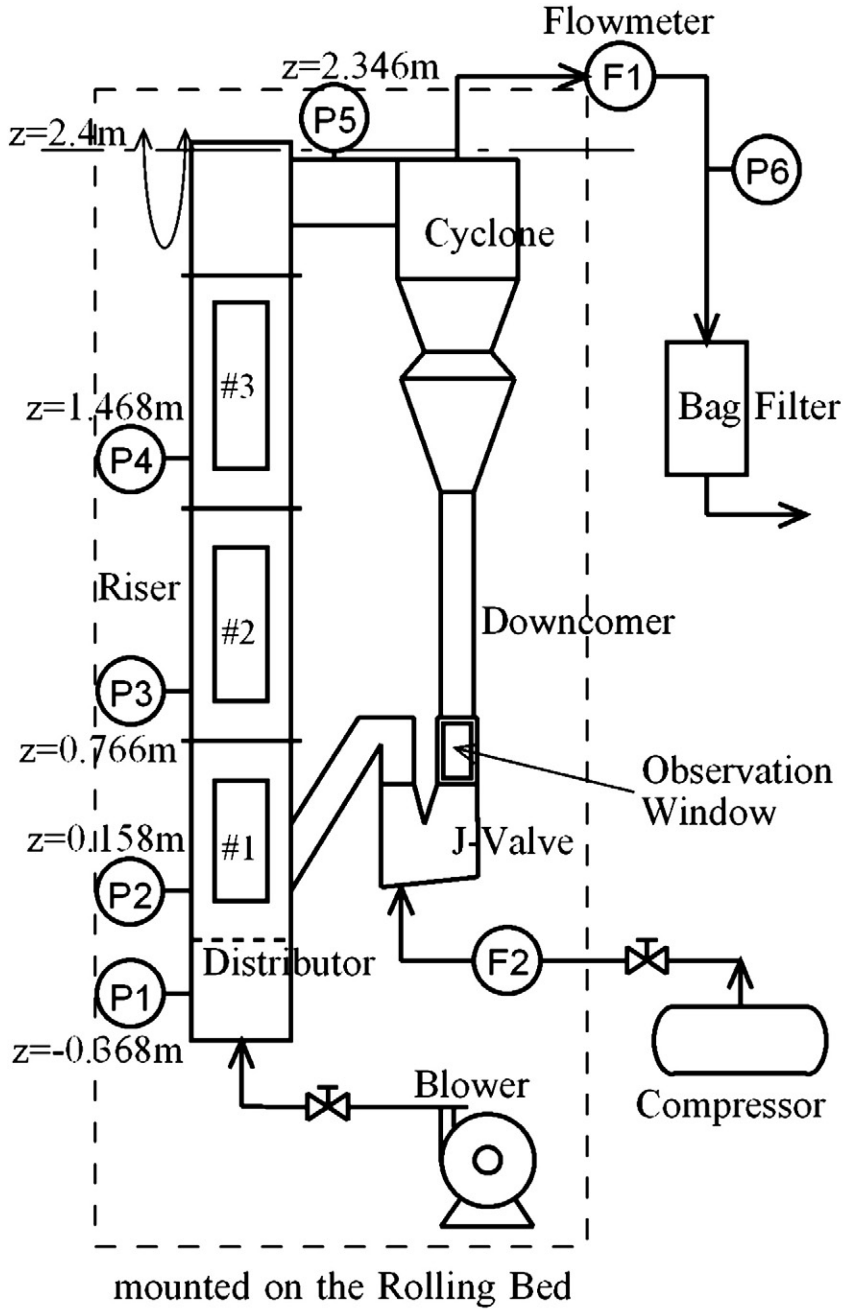

Fig. 1. Test apparatus.

However, to the authors knowledge, no research could be found on the effects of rolling motion on the CFB. To better understand the effects of ship motion on gas–solid flow and heat transfer in the CFB, a series of experiments with a cold model CFB mounted on rolling equipment was performed. In this article, experimental results are presented and the effects of ship motion are investigated.

2. Test apparatus and test conditions

Fig. 1 schematically shows the test apparatus used in the experiment. The part enclosed with broken lines in the figure is mounted on a steel rolling bed. The model CFB is made of steel, and weighs approximately 2 tons. The symbol *z* in the figure denotes the vertical distance measured from the distributor. The cross-sectional area of the riser is 288 mm × 288 mm, and the riser height is 2408 mm. The test apparatus is equipped with six pressure gauges (P1, P2, …, P6) and two orifice flowmeters (F1 and F2). To measure fluid temperature, five platinum resistance thermometers (PRTs) are installed at the wind box, riser, J-valve and the flowmeters F1 and F2. A small amount of compressed air is introduced into the J-valve bottom for aeration. Transparent observation windows are installed at the upper part of the J-valve, where the falling speed of the heaped particles was measured to determine the solid circulation flux *Gs*. Very fine lime particles of two sizes,[1] i.e., 0.18 mm $< d_p <$ 0.35 mm and 0.3 mm $< d_p <$ 0.5 mm, were used as the bed material. The total inventory of the particles and the static bed height at the riser were 40 kg and 175 mm, respectively, in each case.

[1] From the particle size distribution, the Sauter diameters of these particles were estimated to be 0.22 mm and 0.45 mm, respectively.