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The effect of rolling amplitude and period on particle distribution behavior in a rolling circulating fluidized bed

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ABSTRACT

The effect of rolling amplitude and rolling period on particle distribution behaviors in a rolling circulating fluidized bed (RCFB) has been quantitatively clarified by means of the electrical capacitance tomography (ECT) technique. A series of experiments with a cold mode RCFB were performed while the rolling amplitude and rolling period varied from $\Theta = 2.5°$ to $10.0°$ and $T = 5.0$ to 15.0 s, respectively. Based on the particle distribution images captured by the ECT sensor, three main characteristics of particle distribution behavior, namely the average particle volume fraction, the particle distribution stability and the particle distribution uniformity, were quantitatively estimated. As results, the particle distribution behavior in the RCFB was dominated by the shear effect, which was derived from the inertial forces and gravity in the radial direction of the riser. The positive influence of rolling amplitude on the shear effect caused augmentation of the particle volume fraction; however, particle distribution became unstable and heterogeneous. Meanwhile, although the characteristic fluctuation frequency of particle volume fraction was dominated by the rolling period, little effect of the rolling period on the particle distribution behaviors was observed due to its minimal influence on the shear effect.

1. Introduction

Owing to its excellent desulfurization efficiency and heat transfer property, the circulating fluidized bed (CFB) has received considerable attention as a potential choice for the development of a compact and highly efficient marine waste heat recovery system [1]. High particle-gas contact ratio in the CFB improves the interaction between the desulfurization particles and exhausted gases from marine diesel engines and thus solves corrosion problems such as soot-fire by eliminating gaseous sulfur species through a desulfurization reaction [2]. Particle distribution behavior in CFB is a key factor in the gas–solid two phase flow of the circulating fluidized bed, which has significant influence on the gas–solid contact efficiency [3], heat and mass transfer rates [4] and chemical reaction performance [5]. Unlike in its regular application, which is always as a motionless land plant, the whole marine waste heat recovery system that includes the CFB is barge-mounted, and its performance is affected by ship motion, i.e., inclination and rolling.

Because the inclined fluidized bed is a crucial part in certain industrial applications, such as the down-comers of circulating fluidized beds, many published studies have been reported on particle distribution behaviors of the inclined fluidized bed. Valverde et al. [6] investigated the fluidization and sedimentation behaviors of fine cohesive particles in the fluidized bed inclined up to $\Theta = 25°$ from the vertical direction and reported that inclination would promote the fluidization heterogeneity. Martin and Ommen [7] proposed an on-line estimation approach of the overall mass flux in a standpipe with an inclination of $\Theta = 45°$ by means of pressure fluctuation measurements. Pishvar et al. [8] performed a three dimensional simulation of the gas–solid turbulent flow in a fluidized bed under inclination angles from $\Theta = 0°$ to $90°$. Meanwhile, research related to the effect of rolling motion on the particle distribution behavior in a rolling circulating fluidized bed (RCFB) is still scarce. The first approach to this topic was originally motivated by the development of a coal-fired fluidized boiler for marine use. Yasui et al. [9] discussed the flow regimes and heat transfer coefficient in a two-dimensional fluidized bed mounted on rolling equipment. Recently, a series of studies using both cold and heated modes of RCFB were performed by the author's group to better understand the effects of ship motion on the particle distribution and heat transfer behaviors. Murata et al. [10] reported the heterogeneous particle distribution and heat transfer augmentation induced by rolling motion based on pressure drop and local temperature measurement data. Zhao et al. quantitatively investigated the differences in particle distribution behavior [11] and particle-wall heat transfer characteristics [12] between upright CFB and RCFB by means of both experimental and numerical approaches. The periodical variation of the effective forces acting upon

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particles, which include the gas-particle drag force, contact force among particles, gravitational force and inertial force derived from the rolling motion, is proposed to be the primary influencing factor for the heterogeneous particle distribution in the RCFB. However, the rolling amplitude and rolling period were only limited to $\Theta = 15°$ and $T = 5$ s, respectively. Changes of the rolling amplitude and period induce different time-variation features of the effective forces, which affect the particle motion and eventually result in a change in momentum as well as heat and mass transfer characteristics. Therefore, understanding the effect of rolling amplitude and rolling period on the particle distribution behaviors is of vital importance for realistic design and reliable operation of RCFB. Among the commonly used measurement techniques of particle distribution in a fluidized bed, electrical capacitance tomography (ECT) is considered to be the most available tomographic technique because of its high-speed capability, low construction cost, non-intrusive and non-invasive nature [13]. Vast literature on the application of the ECT technique used in fluidized beds demonstrates its capability to observe flow patterns [14] and measure particle distribution behaviors [15].

The present study examines the effect of rolling amplitude and rolling period on the particle distribution behaviors in RCFB. A series of experiments with a cold mode RCFB were performed using different rolling amplitudes and rolling periods. The ECT technique is used to visualize the real-time particle distribution in RCFB. Based on the particle distribution images obtained by the ECT technique, the hydrodynamic properties of particle distribution involving the average particle volume fraction, particle distribution stability and particle distribution uniformity are extracted for different rolling amplitudes and rolling periods. Effects of the rolling amplitude and rolling period on the temporal and spatial particle distribution properties are clarified.

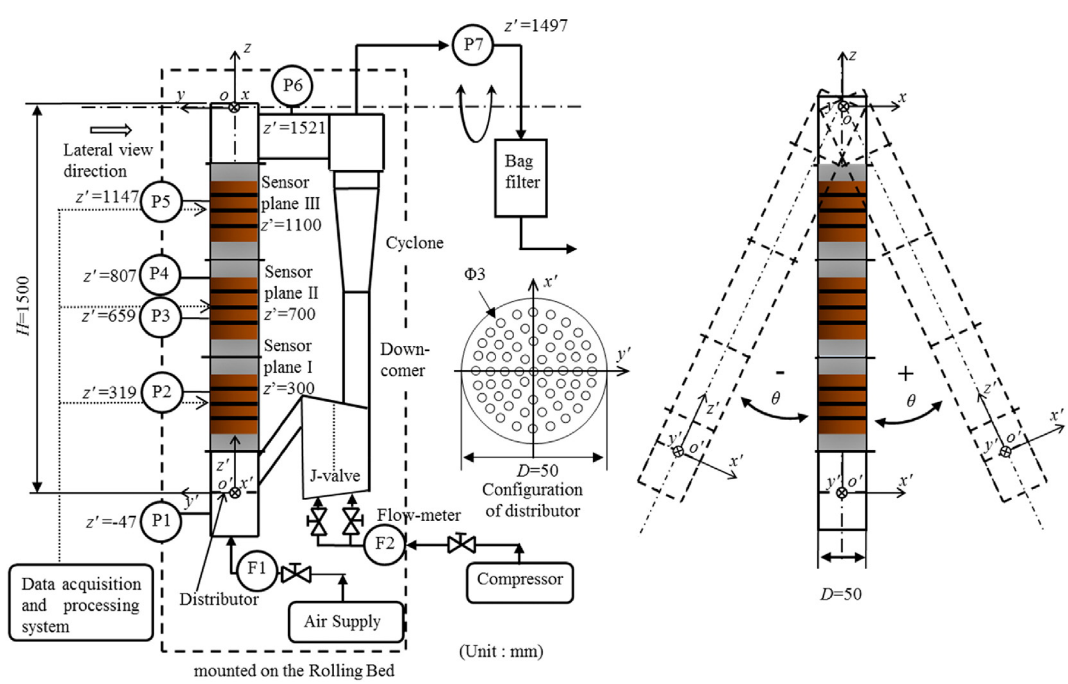
2. Experimental apparatus, method and conditions

2.1. Experimental apparatus

In the present study, as shown in Fig. 1, the experimental apparatus consisted of a riser, a cyclone separator, a down-comer, a J-valve and an air supply system. The riser had an inside diameter of $D = 50$ mm with a multi-orifice distributor at the bottom. The distributor consisted of forty-one even-distributed gas orifices, which were 3 mm in diameter. The average distances between these orifices were approximately 2.5 mm. Compressed air was introduced into the J-valve bottom for aeration. ECT sensor was wrapped around the circumference of the riser at different axial positions to visualize the cross-sectional particle distribution. The ECT sensor used in this study, which consisted of twelve electrodes, was the same as one used in our previous paper [11,16]. Length of the measurement electrode in the ECT sensor was 50 mm. Capacitances between all combination pairs of these electrodes were measured by the data acquisition system to perform an overall scan of the cross-section of the riser and then sent to a personal computer for image reconstruction of particle distribution. Air was used as the circulating fluid instead of the exhaust gas from the marine engine and supplied from the bottom of the riser through the distributor. The experiment apparatus mentioned above was mounted on a rolling bed, which was driven by a servomotor. The central axis of rolling motion was located in the center plane of the experimental apparatus, and it was 1500 mm above the distributor. The experimental apparatus was equipped with seven pressure gauges (P1, P2, …, P7) and two orifice flow-meters (F1 and F2). Two reference frames, a stationary (inertial) reference frame o-xyz and a moving (non-inertial) reference frame o'-$x'y'z'$, are defined as follows. Origin o of the stationary reference frame o-xyz is fixed at the intersection point of the central axis of the rolling motion and the center line of the riser. The y axis of the stationary reference frame is coincident with the central axis of the rolling motion. The moving reference frame o'-$x'y'z'$ rotates together with the riser. Origin o' of the moving reference frame is at the bottom center of the riser, and the z' axis is always coincident with the center line of the riser during the rolling motion. The distance from the rolling axis to the distributor is $R = 1500$ mm. The z' direction is also in the flow direction. The position of the ECT sensor and its investigated region is described in this moving reference frame.

2.2. Experimental method and conditions

As is known, ship movements usually are divided into three types of linear motions (Surging, Swaying and Heaving) and three types of



(a) Front view of the experimental equipment (b) Lateral view of the riser

Fig. 1. Configuration of the experimental apparatus.