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Position and posture determination of a large dense object in a fluidized bed

Rongrong Cai [a,*], Jinlan Qiu [b]

[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, China
[b] School of Electric Power, South China University of Technology, China

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ABSTRACT

An innovative method using a micro-three-dimensional acceleration sensor and a micro-three-dimensional gyroscope to trace the motion behavior of a large object in the dense zone of a fluidized bed is proposed here. By placing a self-designed particle spy module, namely particle tracing sensor (PTS), inside an object, the translational velocity and angular velocity, as well as the posture of the object during the motion process can be detected. The method is validated by testing the displacements of a spherical object with diameter of 40 mm during freefall and by testing its attitude angles during rotation. Then several PTSs, served as object spies delivering in situ information they detect, are utilized to study the motion behavior of spherical and non-spherical objects on the inclined air distributor of a fluidized bed. Findings indicate that the method is capable of tracing the motion behavior of dense objects in the bottom of a bed. The smallest size of the object it can detect is 30 mm × 20 mm × 20 mm and the maximum tracking time is 10 min.

1. Introduction

Simultaneous treatment of dissimilar particles, differing in one or more of their constitutive properties is normally encountered in a fairly large number of industrial applications of gas–solid fluidization technology [1]. Some of these applications involves the motion of large objects within the bed, being fuel particles, catalysts, and agglomerates. These objects may rise in the bubbles, sink with the dense phase, or be stagnant at the bottom bed. Objects' motion patterns and their ability to move throughout the bed have a paramount effect on the performance of the reactors.

Extensive work has been conducted to analyze the motion behaviors of objects immersed in the bed. Some researchers focused on the mixing and segregation processes of binary or ternary mixtures, and found that the hydrodynamic behaviors of particles were strongly influenced by the differences in properties of the respective particles, especially in shape, density and size [2–4]. In these studies, field concentration, velocity and temperature distributions of the mixed particles were obtained from signals arising from the interactions between the field and the external sensor. Doppler particle anemometer (DPA), particle image velocimetry (PIV), X-ray computerized tomography (XCT), laser Doppler velocimeter (LDV), electrical capacitance tomography (ECT), magnetic resonance imaging (MRI) are all the methods in which the external systems provide the incident beams, be that light [5], X-ray [6,7], electrical field [8–10], magnetic field [11], laser [12,13], to interact with the internal material in the field and generate informative signals [14]. Other researchers tried to trace a single particle's trajectory during fluidization in order to analyze its motion behaviors directly [10,15,16]. Limited to the tracing technique, they are always referring to the large particle, namely the object. However, most of them concentrated on the light objects and their vertical motions in dilute zone. Few attentions have been paid on the motion of dense large objects in the bottom bed, which are commonly encountered in solid waste incineration. This is partly due to the lack of reliable experimental methods to observe the motion of individual large objects which are shielded by surrounding neighbors in the bottom bed.

Recently, positron emission particle tracking (PEPT) and computer aided radioactive particle tracking (CAPRT) have been used to obtain the detailed information on the motion of particles in a fluidized bed [17–19]. These techniques use positron cameras to detect the pairs of back-to-back γ-rays arising from annihilation of the emitted positrons, and a location algorithm is applied for calculating the tracer position. They both allow direct measurement of particle trajectories, however, they require high-cost, specialized equipment and sound operating expertise. Another technique reported is magnetic particle tracking (MPT), which

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* Corresponding author.
E-mail address: cerrcai@scut.edu.cn (R. Cai).

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Nomenclature

a	acceleration, m/s^2
C_d	drag coefficient
d	diameter, m
F_b	buoyancy, N
F_d	drag force, N
F_g	gravity, N
g	gravitational acceleration, m/s^2
s	displacement, m
s_r	revised displacement, m
t	time, s
v	translational velocity, m/s
v_r	revised velocity, m/s
w	angular velocity, °/s
Δt	sampling interval, s
ρ	density, kg/m^3
(ψ, θ, φ)	attitude angle

utilizes cheaper Hall-effect sensors instead of the expensive γ-rays detectors to trace neodymium magnets to continuously locate the positions of a single tracer particle over time [20]. This technique also induces certain limitations such as the complexity and limited range of the tracer's bipolar magnetic field. Cai et al. [21] developed an innovative ECT tracing method which is capable of tracing the large objects of different sizes and densities in the bottom bed in a simple and convenient way. While, the measurement accuracy and stability are significantly reduced for large ratio of the object size to bed size. Zhang et al. [22] proposed a new tracing concept, enabling the particles to sense and record the motion information by themselves and send the information to the outside. They encapsulated a micro-three-dimension acceleration sensor into an object to sense the force information, and then the object velocity and displacement were calculated after post-processing. However, they only made a preliminary attempt in this regard. The senor size is too large, and the angular velocity as well as the motion posture of the object could not be detected.

In this study, a micro-particle tracing sensor (PTS), consisted of a three-dimensional acceleration sensor, a three-dimensional gyroscope and Bluetooth wireless technology are designed to measure the in situ motion information of a dense object in a fluidized bed. The PTS can be embedded in the objects with different densities, sizes and shapes, and the in situ accelerations, velocities, displacements as well as the postures of the objects can be directly recorded or calculated. Experiments are performed to validate the effectiveness of the proposed approach.

2. PTS design and performance test

2.1. Design of PTS

The PTS is designed by encapsulating a micro-three-dimensional acceleration sensor, a micro-three-dimensional gyroscope, a microprocessor and a Bluetooth wireless transceiver chip into a small shell as illustrated in Fig. 1. The micro-electro-mechanical system integrates sensors, actuators, electronics and mechanical features in a single microelectronic chip. The three-dimensional acceleration sensor measures the acceleration of the object that it's mounted on. The band pass filter and A/D conversion are carried out for the analogs acceleration signal. It could measure a wide range of acceleration from $-16.0\,g$ to $+16.0\,g$ (g is the acceleration of gravity), and the measurement accuracy is $6.1 \times 10^{-5}\,g$. The three-dimensional gyroscope measures the rotational angular velocity of the object that it is mounted. The rotational angular velocity it measures ranges from -2000 °/s to $+2000$ °/s and the measurement accuracy is 0.05 °/s. The microprocessor is responsible for the signal acquisition and wireless communication circuits control. A micro-cell is installed for the circuit power supply.

In practice, all these modules are embedded and fixed into a shell or into an object directly. By adding other solid material into the shell, or else by altering the shape of the outer shell, various objects of different shapes, sizes and densities can be simulated. It should be noted that the center of mass of PTS should coincide with that of the object. On its center (the center of mass of the object), the angular velocities are measured and the object postures are calculated. Limited to the size of PTS module, the smallest object can be traced is 30 mm × 20 mm × 20 mm. A prototype PMS is shown in Fig. 2.

2.2. Object velocity and displacement calculation

According to the theoretical tracing model, the instantaneous velocity and displacement of the PTS can be calculated by the numerical integration based on the acceleration data from the PTS as

$$\begin{aligned} v(t) &= v(t-1) + \frac{a(t-1)+a(t)}{2}\Delta t s(t) \\ &= s(t-1) + \frac{v(t-1)+v(t)}{2}\Delta t \end{aligned} \qquad (1)$$

where, a, v, s and Δt are the acceleration, translational velocity, displacement and sampling interval, respectively.

Theoretical, the calculation velocity should be zero when the object stops motion. However, due to the existence of the measurement error and the cumulative error from integration process, the integration results of the instantaneous velocity are frequently not zero. Consequently, these errors may eventually cause a huge error on the integration result of the displacement. During the tracing of large dense objects in a fluidized bed, the objects are easily stagnant on the air distributor, and the motion trajectory exhibits strong discontinuity [23]. Therefore, error compensation

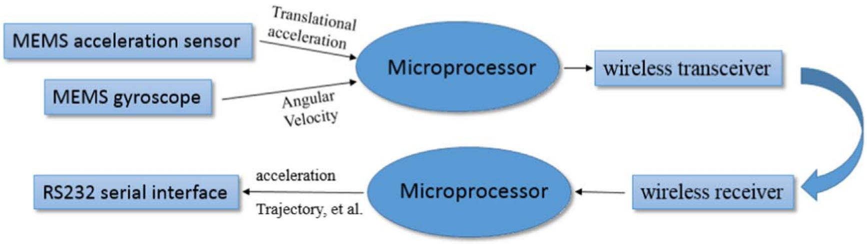

Fig. 1. Design of the PTS.