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Experimental investigation of collision behavior of fluidized solid particles on the tube wall of a graphite evaporator by vibration signal analysis

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ABSTRACT

It is necessary to investigate the collision behavior of fluidized solid particles on the wall of a brittle graphite heat exchange tube of a fluidized bed evaporator for a better fundamental investigation on the vibration risk assessment and heat transfer process enhancement. Vibration acceleration signals of the single graphite tube with an inner vapor-liquid-solid boiling flow at varied steam gauge pressure, solid holdup and particle size were measured with developed signal acquisition and processing system. Main results are as follows. Circulating rate of the vapor-liquid-solid flow, kurtosis and standard deviation of vibration signals were considered as measures of collision force, collision frequency and vibration intensity, respectively. The largest standard deviation occurs in axial middle position of the graphite tube, and kurtosis of vibration signals decreases from the top to the bottom. As the steam gauge pressure increases, the collision frequency of smaller solid particles (1.3, 2.4 mm) increases first and then gradually reaches to a stable value, while a fluctuating or slight decreasing tendency of kurtosis appears for the larger solid particles (3.5 mm). The collision force and the comprehensive vibration intensity factor of all three sizes of solid particles enhance with the increase of steam gauge pressure. As the solid holdup increases, the collision frequency increases obviously, while the collision force decreases. Vibration intensity is higher both with the addition of solid particles and the increase of solid holdup. The boiling coefficient shows a clear enhancement and can be explained according to the conclusions on the collision behavior of solid particles. The results effectively support the reliability of collision behavior research between fluidized solid particles and tube walls by vibration signals analysis, which lays the foundation of reasonable design and further application of the fluidized bed evaporator.

1. Introduction

The shell-and-tube heat exchanger with a vapor-liquid-solid (V-L-S) boiling flow is essentially a fluidized bed evaporator, in which solid particles are fluidized by vapor-liquid boiling flow. Among fluidized bed evaporators, the installation with an external and natural circulating V-L-S boiling flow had especially been investigated due to its stable operation, remarkable heat-transfer enhancement and effective fouling prevention characteristics [1–7]. However, when the solid particles were introduced into the heat exchange tubes in the fluidized bed evaporator and a V-L-S circulating flow was formed, vibration behavior of the heat transfer tube was greatly intensified as an expense of heat transfer enhancement [8,9]. The vibration behavior is actually a reciprocating motion from the stationary position due to transient collision originated from the V-L-S circulating boiling flow [8], and the vibration behavior is elaborately exhibited in the form of vibration signal. The vibration behavior of heat transfer tube is especially obvious in evaporators made of fragile materials, such as impregnated-graphite. The shell-and-tube graphite evaporator was extensively applied in the concentration process of dilute phosphoric acid due to its great thermal conductivity and good corrosion resistance [10]. Nevertheless, strong and persistent vibration behavior can result in fatigue damage even failure of the main heat transfer tube [11]. Therefore, its vibration risk must be systematically assessed as the brittle graphite heat exchange tube exposed to the intense impact and frequent water-hammer environment.

Rudimentary vibration rules and vibration mechanisms of the graphite tube with vapor-liquid-solid boiling flow were studied by the authors [8,9,12,13]. It is found that the vibration components of macro-scale, meso-scale and micro-scale are motivated by the low-frequency circulating boiling flow, the middle-frequency vapor motions, and the high-frequency particle collisions, respectively [8,14]. The attrition

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characteristics of vapor-liquid-solid flow against the walls of the graphite tube in the fluidized bed evaporator were also explored [13]. The mathematical model of the tube vibration was also established, and appropriate operation conditions were suggested by combining the vibration risk and heat transfer enhancement effects [8,9]. In this study, detailed collision behavior of solid particles on the graphite tube walls with a vapor-liquid-solid boiling flow will be further investigated by analyzing measured vibration acceleration signals.

Various signals of the fluidized beds have been measured to investigate the complex hydrodynamics [15–17]. Among them, vibration signal, measured by a non-intrusive method to the inner flow field, is a reliable one because it is highly sensitive to changes of the interaction in the whole frequency range. Considering the non-welding characteristic of graphite material, the vibration technique is finally selected which was measured by accelerometers fixed on the outside surface of the graphite tube with aluminum clamp. In the past a few decades, the vibration signals containing abundant hydrodynamic information have also been extensively processed and analyzed in time, frequency and phase domains to investigate the detail hydrodynamic rules.

One application of vibration signal analysis is hydrodynamics detection of the fluidized bed. Martin and Briongos [18,19] conducted time and frequency domain analyses of low frequency acceleration signals to monitor gas-solid fluidized bed and estimate regime transitions. The hypothesis that low frequency acceleration signals can be used to monitor fluidized beds instead of conventional pressure measurements was proved to be feasible. Researchers in University of Tehran performed a series of experiments in the cold-mold fluidized bed with accelerometers detecting the vibration of the bed. As to the most widely used gas-solid fluidized bed, the output vibration signals over a wide range of operating conditions were analyzed by statistical methods [20,21], power spectral density function [22], auto correlation method [23], Kolmogorov entropy [22]. And the results proved that the vibration analysis technique is a robust method to characterize the hydrodynamics of fluidized bed, such as predicting regime transition velocity [20,22–25], calculating minimum fluidization velocity [20], detecting de-fluidization state [26]. Various statistical and frequency analyses of vibration signals of a gas-liquid bubble columns including both gas and liquid flows were conducted to determine their capability of interpreting bubble behavior inside the columns [27]. The minimum liquid-fluidization velocity of a conventional three-phase gas-liquid-solid fluidized bed was also determined by vibration signals analysis [28].

Another important application of vibration signal analysis is used to realize the real-time measurement of solid phase in natural gas conveying process. Wang and Liu [29] developed a vibration detection device for gas-sand flow and conducted widely experimental investigation. The results showed that there was a good correlation between vibration energy and sand mass flow rate. They also investigated the sand behavior in oil-water-sand multi-phase flow, which lays the foundation for the quantitative particles detection in more complex multiphase flows [30].

However, no effort has been reported on the solid particle behavior characterization of hot-mode vapor-liquid-solid fluidized bed by the vibration analysis technique, which has a great influence on the tube vibration and heat transfer process.

Due to the complexity of the V-L-S fluidized bed evaporator system, hydrodynamics of the V-L-S circulating boiling flow and mechanism of the heat-transfer enhancement process are still not well explained. Several studies were conducted to enhance the basic understandings [1–7]. For example, in the visualization researches, a CCD (Charged Coupled Device) digital image acquisition and processing system with the laser or white light source were developed [31,32]. Axial distributions of solid holdup and velocity, axial circulating velocity of the V-L-S flow, and the heat transfer coefficient in a transparent installation were studied. Most of the studies mainly focused on axial particle distributions along the heat exchange tube due to the limitation of the measuring methods of conventional pressure signal and camera recordings, but it is to be observed that the heat transfer process happened in the heated tube is a radial process, which puts forward another demand, beside vibration risk of the bed, on research of detailed interaction between solid particles and tube walls.

In this study, a V-L-S flow boiling fluidized bed evaporator mainly made of a single graphite heat exchange tube was built and related experiments under extensive operational conditions were carried out. The paper mainly consists of three parts. The sensitivity of vibration signals to solid particles behaviors will be first determined by time series and power spectrum analyses of vibration signals. Then the collision force, collision frequency and integral impact effect will be investigated according to the circulating rate of V-L-S boiling flow, kurtosis and standard deviation of vibration signals at different experimental conditions. Finally, heat transfer characteristics of the fluidized bed evaporator will be analyzed and explained according to the relevant results of collision behaviors of solid particles.

2. Experiment and data processing methods

2.1. Experimental installation and process

The experimental installation and data acquisition system are shown in Fig. 1 [8,12-13]. Experiments were conducted in a laboratory scale V-L-S external circulation fluidized bed evaporator, whose main component is a double-pipe heat exchanger. The inside tube (5) is made of impregnated-graphite with tube diameter of 0.037×0.006 m and length of 1.1 m, and the outside tube (6) is made of stainless steel with diameter of 0.159×0.003 m. The circulating tube (9) is consisted of visual window, spring and stainless tube. Distilled water was used as liquid phase and glass beads with density of 2500 kg/m^3 and diameter of 0.0013, 0.0024 and 0.0035 m were used as solid particles phase.

The saturated steam, produced from the electronically heated boiler (1), condensed in the annular space between the inside tube (5) and the outside tube (6). The latent heat was absorbed by the liquid at ambient temperature and average density in the heated graphite tube was decreased along with the rise of temperature. The density difference between the circulating tube (9) and the heated graphite tube (5) offered the driving force of the circulating flow without any power apparatus. The density difference was further increased when there are many generated vapors in the heated tube at the boiling point. With the fluidization of added solid particles by the circulating liquid, a steady V-L-S circulating boiling flow was formed. The V-L-S boiling flow flowing from the graphite tube (5) was separated in the separator (7), and after that the vapor moved into the vapor condenser (15) and the liquid-solid mixture phase flowed back to the circulating tube (9). The added holdup of solid particles ranges from 0 to 2.0%. The gauge pressure of heating steam ranges from 70 to 150 kPa.

2.2. Parameter measurements and data acquisition and processing systems

Vibration signals of the graphite tube were collected by the shear type piezoelectric accelerometer (2107 CM in type, Yangzhou Mike Company, china) with a sensitivity of 52.6 pc/g and a measuring range of $\pm$10,000 m/s^2. The measuring points are named measuring point X ($H/L = 0.75$), Y ($H/L = 0.50$) and Z ($H/L = 0.25$) from the tube top to the bottom, respectively, as shown in Fig. 1. The dynamic signal test and analysis system (TST5915 in type, Jiangsu test electronic equipment company, China) was used to acquire vibration acceleration signal with the sampling frequency of 5000 Hz. At each run, the data were recorded for 30 s.

External strike experiments on the graphite tube were conducted to simulate the inner collision behavior between solid particles and tube walls, and response spectra of the graphite tube were observed for the determination of proper sampling frequency. The set of sampling frequency is completed by pre-collection process and sampling frequency determination two stages. In the pre-collection stage, the pre-sampling frequency was gradually increased until the frequency spectra were clearly shown and the primary response spectra kept stable. Finally