Powder Technology 291 (2016) 201–213

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Multi-scale vibration behavior of a graphite tube with an internal vapor–liquid–solid boiling flow

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ARTICLE INFO

Article history:
Received 29 August 2015
Received in revised form 15 December 2015
Accepted 21 December 2015
Available online 23 December 2015

Keywords:
Fluidized bed evaporator
Graphite tube
Vibration
Wavelet
Power spectrum

ABSTRACT

In this study, a fluidized bed evaporator mainly made of a brittle graphite heat transfer tube was developed and the vibration acceleration signals of the tube were measured by means of accelerometer sensors and datum acquisition systems at varied steam pressure, solid holdup, particle diameter and axial position to investigate the vibration characteristics of the tube induced by an internal vapor–liquid–solid boiling flow. Multi-scale characteristics of the vibration acceleration signals are identified by the power spectral density and wavelet transformation analyses. The high (3000–9000 Hz), intermediate (500–3000 Hz) and low (0–500 Hz) frequency components of the signals are motivated by the micro-scale motion of solid particles, meso-scale motion of vapor bubbles and macro-scale motion of the circulating liquid flow, respectively. The axial distributions of solid particles and vapor bubbles in the opaque graphite tube can be well reflected by the power spectral density analysis. The tube vibration energy enhances with the increase of solid holdup. Especially, the energy of the micro-scale vibration sub-signal gradually rises and then dominates the system with solid holdup. However, the energy of the micro-scale sub-signal shows a slight increase with heating steam pressure due to the uniform axial distribution of solid particles. The influence of particle diameter is mainly reflected in the enhancement of micro-scale motion. In order to balance the possible destruction caused by tube vibration and heat transfer enhancement due to the addition and fluidization of solid particles, operating conditions of lower solid holdup and higher steam pressure are recommended for the industrial application of vapor–liquid–solid fluidized bed evaporators.

1. Introduction

The vapor–liquid–solid (V–L–S) evaporator, as a type of fluidized bed heat exchanger, in which solid particles are fluidized by vapor–liquid boiling flow, features enhancement of heat transfer and inhibition of fouling in place. The fluidized bed evaporator has been applied to several process industries [1–11]. Now it is going to be used in the evaporating concentration process of dilute phosphoric acid. However, in the available evaporators for dilute phosphoric acid, heat exchange tubes are often made of brittle graphite materials due to their better corrosion resistance and higher thermal conductivity [12,13]. In this situation, it is necessary to evaluate the vibration risk or security of heat exchange tube due to the addition of solid particles into the evaporator, because graphite tube is not suggested for the situations with strong vibration, high pressure and frequent shock in consideration of its brittle nature [13].

However, the investigations on tube vibration behavior induced by internal multi-phase flow are seldom reported, especially on the vibration behavior of graphite tube with internal V–L–S boiling flow. This study will focus on this area.

The vibration failure of heat exchange tubes is still a big concern in the design, operation and control of heat transfer installations. Indeed, it is a complicated problem and has been extensively studied in the fluid–structure coupling field. Chen [14] and Sukauskas and Katinas [15] studied the fluid dynamic forces acting on heat exchanger tubes. The fluid–structure coupled models and the coupled mechanisms, such as Poisson coupling, junction coupling and friction coupling have also been suggested [16–19]. Researches on vibration of heat exchange tubes motivated by shell side cross-flow can be traced back to the work by Khulief et al. [20]. Weaver et al. [21] also summarized the researches on heat exchanger vibration condition caused by shell side fluid flow.

Vibration behaviors of the graphite tube were detected by the piezoelectric accelerometer and then vibration signals were obtained by means of a datum acquisition system. Therefore the vibration rules and vibration mechanism can be studied by the analyses of vibration signals, such as power spectral density (PSD) analysis and wavelet transformation (WT) analysis.

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http://dx.doi.org/10.1016/j.powtec.2015.12.025
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PSD analysis has been widely used in the frequency domain analysis of the detection signals in fluidized beds, such as, pressure signal [22], vibration signal [23], and conductivity signal [24]. For instance, Shou and Leu [22] proved that the energy of PSD of pressure signals could be a new alternative method in identifying the transition velocities and flow regimes in gas–solid fluidized beds.

Multi-scale phenomenon widely existed in the multi-phase systems due to the nonlinear interactions among different phases [25–26], and can be investigated by dividing the global signal into several signals of different scales. Wavelet decomposition, as a time–frequency analysis method, has been used to extract multi-scale information from the global signals in multi-phase systems for better identifying the minimum fluidization velocity [24], the transition velocity [27], fluidized bed hydrodynamics [28] and bubble behaviors [23]. Ren et al. [29] decomposed dynamic signals acquired by a fiber optical probe in a gas–solid fluidized bed into three-scale components: micro-scale component (particle size), meso-scale component (cluster size) and macro-scale component (unit size). Abbasi et al. [30] also extracted three-scale sub-signals from the global vibration signal in a gas–solid fluidized bed, the micro-scale sub-signal related to particle–particle or particle–wall interaction, meso-scale sub-signal corresponded to motions of small bubbles, and macro-scale sub-signal linked to large bubbles.

The main objective of this study is to explore the vibration rules and vibration mechanism of a brittle graphite tube with internal single-phase liquid flow, vapor–liquid boiling flow and V–L–S boiling flow by PSD and WT analyses of vibration acceleration signals. Effects of heating steam pressure, solid holdup, particle diameter and tube axial position on vibration behaviors were also discussed. Optimized operating conditions were suggested with the balance of vibration risk and heat transfer benefit. The concrete analysis process is explained below.

2. Experimental installation, parameter measurements and data processing methods

2.1. Installation and measurements

The experimental installation is illustrated in Fig. 1. The apparatus is an external natural circulating fluidized bed evaporator. The main test section was a double-pipe heat exchanger. Its inner tube was made of graphite material with an outside diameter of 0.037 m, wall thickness of 0.006 m and tube length of 1.1 m. The outer tube was made of stainless steel with the outside diameter of 0.159 m, wall thickness of 0.003 m and tube length of 1.1 m. Distilled water was used as liquid phase and glass beads were used as solid phase with an average diameter of 1.3 mm, 2.4 mm and density of 2500 kg/m^3.

Vibration experiments and parameter measurements were performed in such a system at different operating conditions. Saturated steam, condensed in the annular space between the outer and inner tubes, was used as heating medium to heat the liquid (solid) phase inside the graphite tube. The liquid (solid) phase absorbed the latent heat and boiled to vapor phase. The density difference of fluid mixtures between the heated tube and the circulating tube resulted in a V–L–S external natural circulating boiling flow. The V–L–S flow, coming from the top of the heated tube, entered into a vapor–liquid (solid) separator; afterwards the vapor phase entered into the vapor condenser and condensed to liquid phase. While the L–S flow leaving the separator was pumped back to the circulating tube to start a new circulation [11].

Vibration signals were acquired by the piezoelectric accelerometers with a sensitivity of 52.6 pc/g, and then were recorded and analyzed by the dynamic signal analysis and processing system (Jiangsu Test Electronic Equipment Company). Due to the brittleness and non-welding characteristics of graphite material, three accelerometers were adhered to the outside wall of the graphite tube in equal axial distance by three aluminum clamps, named measuring point X (H/L = 0.75), measuring point Y (H/L = 0.5) and measuring point Z (H/L = 0.25) from tube top to bottom, respectively. The sampling frequency (f_s) of vibration acceleration signal was set to 20 kHz according to the Shannon–Nyquist criterion, and sampling time was 360 s in each run.

Metal foil surface thermocouples (Model: 20109, American RdF Company) were used to measure the outer surface temperature of the graphite tube. They were pasted on the graphite tube to capture the transient wall temperature real-timely and accurately. Grade I armored-T type thermocouples (Shenyang Zhongse Instrument Company) were used to measure the internal fluid temperature corresponding to measuring points X, Y and Z. The linear correlation coefficients of calibration curves for all the thermocouples were above 0.999. Two MC20W sanitary type pressure transmitters were implemented to measure the pressure value at the inlet and outlet of the graphite tube. An electromagnetic flowmeter (model: EMF8101(50)12100C11) was used to measure the volume flow rate of the multi-phase flow with the accuracy grade of 0.5 and the full scale of 10 m^3/h. All the signals were recorded and analyzed by JM3840 static and dynamic signal

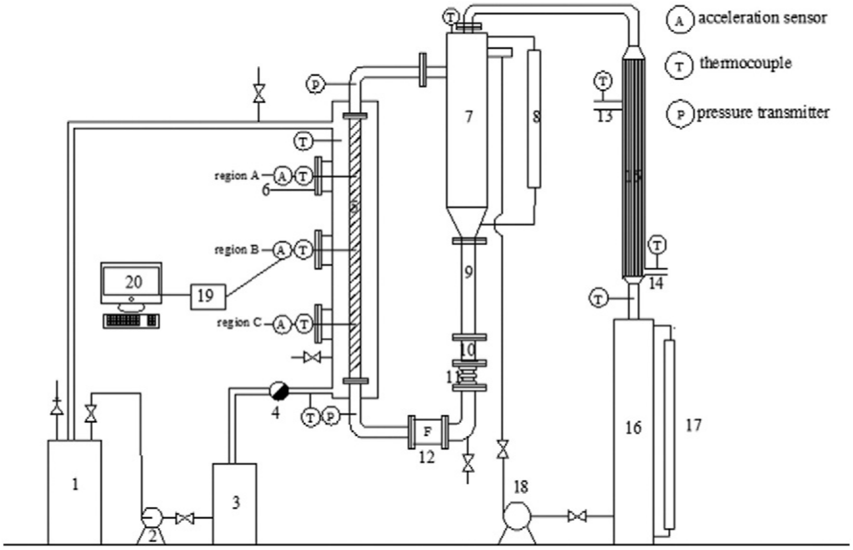

Fig. 1. Apparatus and flow diagram of V–L–S flow boiling evaporator. 1 — Boiler; 2 — centrifugal pump; 3 — steam condensate tank; 4 — steam trap; 5 — graphite tube; 6 — shell side of heater; 7 — separator; 8 — level gauge; 9 — circulating tube; 10 — visual section; 11 — spring; 12 — electromagnetic flowmeter; 13 — outlet of cooling water; 14 — inlet of cooling water; 15 — vapor condenser; 16 — vapor condensate gauge tank; 17 — level gauge; 18 — magnetic drive pump; 19 — data acquisition system; 20 — PC.