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Nonlinear behaviors of vibration acceleration signals in a graphite tube with vapor-liquid-solid boiling flows

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ABSTRACT

The vibration signal is seldom applied to study the nonlinear characteristics of the fluidization system with boiling flows even though it is very important to understand the vibration behavior of the system. In this paper, the multi-value phenomenon of correlation dimension and its relationship with multi-scale flow behavior were investigated based on the chaotic analyses of the vibration acceleration signals as well as pressure drop signals measured from a single graphite tube in the vapor-liquid-solid fluidized bed evaporator. With wavelet decomposition and signals reconstruction techniques, the characteristics of the medium and low frequency signals are displayed. Nonlinear vibration behavior in multi-phase boiling flow system was analyzed at varied solid holdup and steam gauge pressure. The influence of solid particles on the correlation and regularity of the motion of the system is more obvious than that of the steam pressure. Three-scales were obtained, namely the macro-scale, meso-scale and the micro-scale, respectively. It is an effective method to characterize the multi-scale behavior in the multi-phase fluidized bed evaporator by measuring and analyzing the vibration acceleration signals.

1. Introduction

The fluidized bed evaporator with an external natural circulation vapor-liquid-solid (V-L-S) boiling flow has been successfully used in chemical, pharmaceutical, environmental and other process industries because of its online fouling prevention and heat transfer enhancement features.

It has been reported that the dynamic systems of vapor-liquid (V-L) [1–4] and V-L-S external natural circulation boiling flows [5–6] exhibit chaos characteristics. The dynamic system which exhibits chaotic behavior often has a strange attractor [7], which can be characterized by several chaos invariants. One of the most commonly calculated parameters of a chaotic attractor is the correlation dimension. The correlation dimension indicates the complexity of the structure in phase space. Correlation dimension D_2 is such a typical invariant [8], the value of which is close to the independent variable number of the system or the number of freedom degrees of the system. A high correlation dimension D_2 corresponds to a highly complex attractor with many degrees of freedom. However, it should be noted that chaos theory does not provide information on which are the variables that completely describe the physical phenomena [9].

According to the results of chaos analysis of time series in the systems of multi-phase flows, the flow regime can be characterized and quantified by the chaos invariants, and in a certain range of operating conditions the chaos invariant has a multi-value feature [5,10–13]. The multi-value phenomenon of the chaos invariant for the multi-phase system has its intrinsic physical sources, such as due to the multi-scale behavior [14]. An appropriate implication of such a multi-scale behavior would be useful for understanding the complicated structure of multi-phase flows. However, previous data processing methods either give one value of the chaos parameter in order to analyze the varying tendency, ignoring the multi-value phenomenon and useful information, or fail to explain the rich variety of information available across all the scales and only give some values of the chaos parameter according to the comprehension of the authors, which is not convenient for tendency analysis [10]. Liu et al. [10] found that when a bubble column is in the homogeneous flow regime, only one correlation dimension can be obtained. The multi-correlation dimensions can be obtained in the heterogeneous churn flow regime. Studies on chaos characteristics in gas-liquid bubble columns have also been carried out by Liu and Cassanello [15,16]. Liu et al. [5] investigated the chaos characteristics in vapor-liquid-solid boiling flow evaporator by using the temperature fluctuations of the bed, and found the multi-value phenomena. The chaotic dynamics in the multi-phase (however, not V-L-S boiling) flow system have been determined by analyzing the pressure drop or the pressure fluctuations of the beds [17–21].

Vibration signal can be a good representation of the overall hydrodynamics of the fluidized beds. Vibration signals originate from the behavior of bubble motions, solid particles and particle-wall collisions within

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the fluidized beds [22]. A vibration monitoring technique has been used to study the hydrodynamics of a gas-solid fluidized bed [23–25] such as bubble behavior and regime transition. The minimum liquid-fluidization velocity was determined and the dual effect of solid particles on the local hydrodynamics in a gas-liquid-solid fluidized bed [26] was investigated by the means of vibration signal analysis. Vibration acceleration signal was used by Ma [27] to analyze the vibration characteristics of a brittle graphite tube with V-L-S boiling circulating flows at varied solid holdup, particle size, and steam pressure, preliminarily. Furthermore, An et al. [28] explored the vibration rules, vibration mechanism and multi-scale characteristics of such a system by wavelet transformation and power spectral density analyses.

Vibration signal analysis may also be an effective method to characterize the chaotic dynamics of the V-L-S boiling flow. However, little work has been done. The emphasis of this study is on the investigation of the applicability of tube vibration acceleration signal analysis, in comparison to the pressure drop, to study chaotic behavior of the fluidized bed with vapor-liquid-solid boiling flows. The focus is mainly on the multi-value phenomenon of correlation dimension and its relationship with the multi-scale flow behavior at varied solid holdup and steam gauge pressure.

2. Experimental

The experimental installation is schematically shown in Fig. 1 [28]. Experiments were conducted using an external naturally circulating fluidized bed evaporator. The test section consisted of a 0.037 × 0.006 m diameter by 1.1 m length impregnated-graphite tube. Water was used as the liquid phase and glass beads with density of 2500 kg/m^3 and diameter of 0.0024 m were used as the solid phase.

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 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 [5].

An accelerometer installed in the center of the graphite tube was used to measure the vibration response of the graphite tube. The sampling frequency was 5000 Hz and the total sampling time was 60 s. Two pressure transmitters were used to measure the inlet and outlet pressures of the test section, and to obtain the pressure drop. The sampling frequency of pressure signals was 200 Hz. The accelerometer and pressure drop fluctuation signals were measured simultaneously [29]. The experiments and measurements were repeated twice under the same operational conditions to ensure a good repeatability.

Before the chaos analysis of time series, several parameters are determined. These parameters such as the embedding dimension and time delay are chosen carefully and the number of the points of experimental data is sufficiently large to reach the linear independence of the phase space coordinates and reduce the effect of autocorrelation of the data [10]. The time delay is usually selected with respect to an autocorrelation function of the data [30]. In this work, the time delay of the pressure drop signal was 0.03 s and changed with the size of the solid particles. The time delay of acceleration signal was 0.0004 s. The issue that how many points are enough for chaos analysis has been widely discussed. Most studies have shown that 3000 to 10,000 points are sufficient for the multi-phase flow systems [10]. The number of points in this work was 10,000. No significant improvement of chaotic invariant calculation was obtained when a larger number of sampling points was adopted. The average value of the time series was subtracted from the original signal before chaos analysis. In this way, only the fluctuating component is considered [12].

3. Results and discussion

3.1. Original signal

3.1.1. Time domain analysis

When the solid particles were added into the graphite tube with V-L boiling flow, a V-L-S boiling flow was finally formed. Typical vibration acceleration and pressure drop signals of graphite tube with V-L and V-L-S boiling flow under heating steam gauge pressure p of 110 kPa

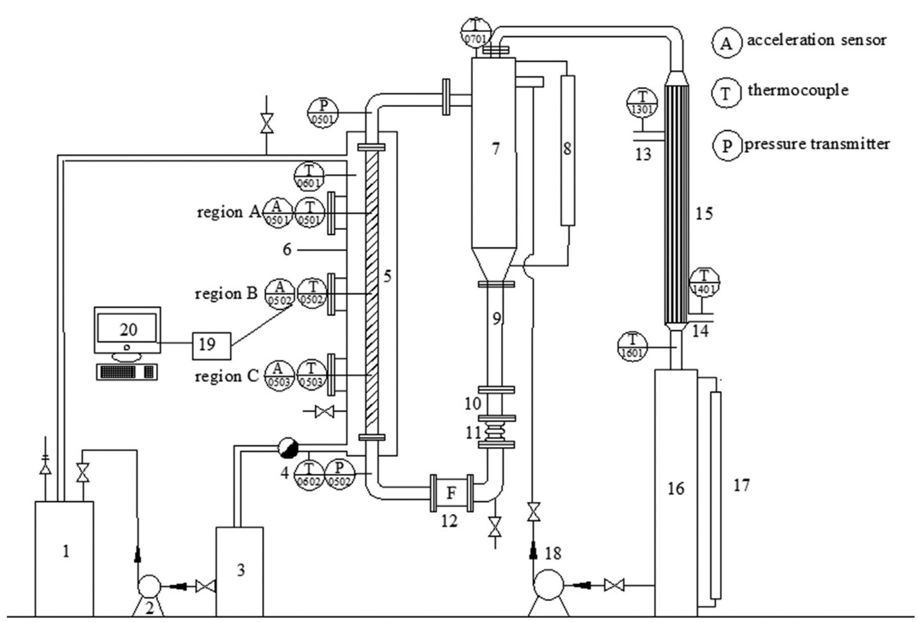

Fig. 1. Apparatus and flow diagram of a graphite tube fluidized bed evaporator with vapor-liquid-solid external circulating flow and measuring system of vibration signal [28]. 1-Boiler; 2-centrifugal pump; 3-steam condensate tank; 4-steam trap; 5-graphite tube; 6-shell side of heater; 7-separator; 8-level gauge; 9-circulating tube; 10-visual window; 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; 0502A-acceleration sensor in the middle of the graphite tube; 0501P-pressure transmitter at the outlet of the graphite tube; 0502P-pressure transmitter at the entrance of the graphite tube.