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Chaotic characteristics in an evaporator with a vapor–liquid–solid boiling flow

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Abstract

In this paper, quantitative and qualitative investigations on the unstable fluctuations of wall temperature signals in a multiple-tube evaporator with a vapor–liquid–solid boiling flow were carried out by employing the nonlinear analysis tools including reconstructed phase space analysis, correlation dimension analysis and Kolmogorov entropy analysis besides the traditional analysis methods such as power spectral analysis and autocorrelation analysis. The values of Kolmogorov entropy are positive and finite, and the values of correlation dimension are from 1.5 to 2.0. The analysis results indicate that the physical parameter fluctuations of the system with a vapor–liquid–solid three-phase boiling flow are chaotic. Based on the estimates of correlation dimension, it can be found that at least two independent variables are needed in order to describe the flow boiling behavior of such system. The curve shapes of correlation integral versus radius of hypersphere vary with the variations of multi-phase flow regimes or states. So do the curve shapes of slope or Kolmogorov entropy versus radius of hypersphere. And the multi-phase flow regimes or states at given operation conditions in such system may be identified or characterized by the shape variations of these curves. In the estimations of chaotic invariants including correlation dimension and Kolmogorov entropy at the same given operation condition, the multi-value phenomena are found. The phenomena reflect the multi-scale behavior occurred in such multi-phase flow boiling systems.

Keywords: Vapor–liquid–solid flow; Three-phase flow; Flow boiling; Evaporation; Nonlinear analysis; Deterministic chaos; Correlation dimension

1. Introduction

Adding some solid particles into an ordinary evaporator can enhance the evaporation process and prevent the fouling formation on the surface of heated tubes. A new type evaporator with a vapor–liquid–solid (V–L–S) boiling flow is built in this way. The evaporator is successfully being used in chemical engineering, pharmaceutical and other process industries [1–3]. However, the fluctuation phenomena of physical parameters were often observed in the running of such installations, like in traditional ones. The quantitatively predictions of flow and heat-transfer characteristics of such systems are still difficult.

Recently, deterministic chaos analysis technique has been used to analyze the nonlinear behavior in two-phase boiling flow systems and some new mechanisms have been disclosed [4–7]. However, little work has been done on the system with V–L–S boiling flow. The three-phase boiling flow is by nature out of equilibrium, stochastic and complex. Hence, it is necessary to analyze its complex behavior from the point of view of dynamic systems by applying the nonlinear analysis tools.

In this paper, the nonlinear features of wall temperature fluctuations in V–L–S boiling flow are investigated by means of deterministic chaos analysis technique to provide deeper understanding on the flow and heat transfer mechanisms. The work is of importance to the design, operation and control of such installations.

2. Experimental setup

In order to investigate the complex behavior often observed in industrial facilities, an experimental multiple-tube evaporator was built, consisting of four heated vertical stainless steel tubes. The outer diameter of each heated tube is 38 mm with the inner diameter of 32 mm. Liquid phase was tap water, and solid phase was Teflon cylindrical particles with both diameter and length of 3 mm and density of 2190 kg/m^3. The experimental setup is illuminated in Fig. 1.

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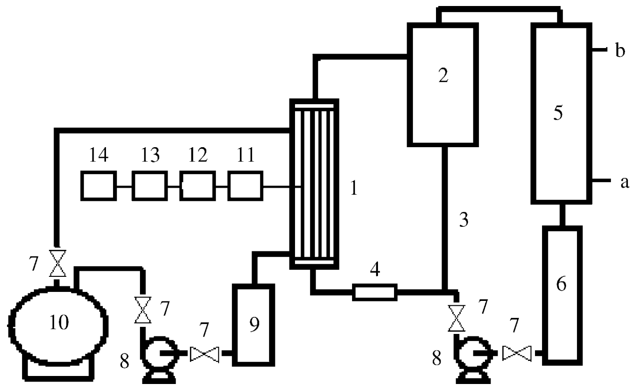

Fig. 1. Experimental apparatus and flow diagram. (1) Heat exchanger; (2) separator; (3) circulating tube; (4) electromagnetic flow-meter; (5) vapor condenser; (6) vapor condensate gauge bank; (7) valve; (8) liquid pump; (9) condensate gauge bank; (10) boiler; (11) thermocouple probe; (12) ample plate; (13) A/D plate; (14) PC. (a) inlet of cooling water; (b) outlet of cooling water.

In an ordinary evaporating operation with a V–L boiling flow, no solid particles were added into the evaporator. At the beginning of an experiment with V–L–S boiling flow, the liquid and solid particles were added into the evaporation system. During the evaporating, the condensation latent heat of the boiler steam in shell-side space was used to heat the mixture in tube-side space or in heated tubes in a shell-and-tube heat exchanger. The boiler steam was condensed from vapor phase to liquid phase and was collected in a condensate gauge bank. Then, the steam condensate was pumped back to the boiler by water pump after its volume flow rate was gauged. The V–L–S mixture in the upper part of the heated tubes got into the separator in which the vapor and liquid–solid (L–S) mixture separated. The produced vapor was condensed in a shell-and-tube vapor condenser by cooling water in shell-side space. Then the vapor condensate was collected in a vapor condensate gauge bank, where the volume flow rate was measured to get the heat-transfer rate or the heat flux. The L–S mixture in separator circulated back to the bottom of the heat exchanger through the circulating tube and electromagnetic flow meter. And the L–S mixture was heated by boiler steam again. The liquid levels in separator were kept the same for different runs and no additional liquid phase was supplied during the datum samplings and measurements. The whole system was operated in a model of an external natural circulating flow and at a atmospheric pressure. The control parameter of the system is the pressure of boiler steam or the steam temperature. Thus, for each run, the temperature was constant. The properties of solid particles and operation conditions are shown in Table 1.

When the boiler steam pressure and thus the rate of heat transfer was very low, no vapor–liquid (V–L) circulating flow was formed because the boiling phenomenon did not appear in the heated tube. With the increase of steam pressure, the circulating flow was gradually established by the density difference between the V–L mixture in heated tube and the liquid in circulating tube. However, no V–L–S circulation flows were obtained when the steam pressures were relatively low because in this operation condition, the circulating velocity of V–L mixture was lower than the terminal velocity of added solid particles as well. When the heat-transfer rate or the heat flux reached a certain high value, a typical V–L–S circulation flow could be obtained. The experimental data were sampled when the three-phase circulating flow was established.

A precise measuring system aided by a personal computer for on-line automatic measuring and sampling was developed to obtain the data of wall and fluid temperatures. Wall temperatures of heated tubes were measured by means of copper–constantan thermocouples with the wire diameter of 0.2 mm, and fluid temperatures of the system were measured using the armored copper–constantan thermocouples with the diameter of 1.5 mm. The profile of the four heated tubes in heat exchanger and the distribution of the thermocouples in each heated tube when measuring the wall and fluid temperatures were shown in Fig. 2. The system uncertainties are mainly associated to the calibration of the thermocouples, the amplifier, data acquisition and reduction systems besides the thermal resistances between thermocouples and tube walls. The dynamic error of the temperature measurements is negligible for the response time of the thermocouples is at least three orders of magnitude lower than the studied fluctuations of temperatures. The overall uncertainty of the temperature measurement is 1 °C, with 95% confidence level. The measured signals obtained from the probes were amplified, digitalized and stored in a PC for further processing. The sample frequency is 125 Hz, and the sample time is 80 s. It is well known that the measured original signals often contaminated by low amplitude and high frequency noise. Hence, measures should be taken to reduce the noise. For most wall temperature signals, the main frequency and most meaningful frequencies are less than 15 Hz. This can be got from the power spectrum of original wall temperature signal in linear coordinates (not given here). In order to reduce the noise and at the same time to ensure that the spectra of interest of the signal were still captured, the signals were filtered with a frequency of 31.25 Hz ($\geq 2 \times 15$) using a low-pass algorithm (the input parameter is 125/4) before executing the datum treatment. This treatment of noise reduction is similar to that of most studies on the chaos analysis of signals.

The total pressure drops between the inlet and the outlet of the heated tubes and circulating flow rates of the mixture in heat exchanger were also measured by differential pressure transducer and electromagnetic flow meter, respectively.

In the following analyses, the time series of wall temperature measured at the top of the left heated tube is used to judge the system either chaotic or not, and to explore the variations of chaos invariants with the operating conditions. Here, the holdup of solid particle, $\epsilon = 1\%$ is taken as an example. The solid holdup is the ratio of the volume of solid particles to the total volume of the three-phase mixture. The height of the three-phase mixture in this evaporator is kept along the horizontal centerline of the

Table 1
Properties of solid particles and liquid and operation conditions

Particle parameters		Operation parameters	
Diameter × length (mm × mm)	Density (kg/m^3)	Steam gauge pressure (MPa)	Average volume holdup (%)
3 × 3	2190	0–0.15	0–4