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Chaotic forecasting of time series of heat-transfer coefficient for an evaporator with a two-phase flow

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Abstract

The time series of heat-transfer film coefficient for an evaporator with a vapor–liquid two-phase boiling flow were forecasted by the chaotic prediction or the local nonlinear short-term prediction. The forecasting method was based on the phase space reconstruction theory and a mathematic model in the form of datum driving had been developed to carry out the prediction. The signals of heat-transfer film coefficients predicted by this method were compared with those obtained from the experimental measurements. Different from the previous work, the comparisons in this work were done both from the point of view of the time trajectory and from the point of view of macroscopic or general characters. Besides the time-averaged statistics characteristics, such as the average value, average deviation and standard deviation, the power spectrum, phase plane map and chaotic invariants including the correlation dimension and Kolmogorov entropy had been calculated and been compared for the time series obtained both from the experimental measurement and from the forecast. The comparison for each parameter between the value calculated from the time series measured and that estimated from the time series forecasted by the chaotic forecast method shows satisfactory agreement. The limited length in time with an accuracy prediction indicates that the system is chaotic. The agreement of the comparison of the general parameter indicates that the chaotic prediction is effective for the estimations of the heat transfer characteristics of the two-phase flow boiling system and that the chaotic prediction method may be a potential tool for the effective thermo-fluid control for such evaporators.
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Keywords: Vapor–liquid boiling; Heat transfer film coefficient; Chaos; Chaotic prediction; Evaporator

0. Introduction

The evaporator with vapor–liquid two-phase boiling flow is an important installation and is widely used in chemical, petrochemical, power and energy industries. However, it is still difficult to describe quantitatively its flow and heat transfer behavior due to the extreme complexity of flow boiling system. Recently, the nonlinear points were introduced to the boiling system to unravel the mechanism and to suggest some potential reasons why only limited success were achieved in the mechanistic modeling of boiling.

Many nonlinear studies reported in open literature focused on pool nucleate boiling system due to the simple configuration from which it was easy to address fundamental issues and was reviewed recently by Shoji (2004). Sadsivan et al. (1995) investigated the nonlinear effects in pool nucleate boiling heat transfer with high heat flux by simple numerical experimentation. The results demonstrated qualitatively that the on–off nonlinear behavior of the nucleation sites on the surface is the source of the nonlinear behavior and the nonlinear effects are responsible for some of the data scatter commonly seen in boiling data. Chai and Shoji (2001) studied the pool boiling curves by the catastrophe theory and found that the transition of pool boiling modes is virtually corresponded to the bifurcations. Shoji and Takagi (2001) investigated the bubbling features from a single artificial

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cavity. In their work, conical, cylindrical and reentrant cavities were manufactured on a thin Cu plate and were heated by laser in a saturated water pool. Reconstructed phase map from temperature time series revealed the nonlinear behavior of bubbling, and the analysis showed strong possibility of low-dimensional chaos. In their later work (Chai and Shoji, 2002a,b), the self-organization and self-similarity in pool boiling systems were investigated based on non-equilibrium thermodynamics and found that boiling system is a typical open dissipative structure. The criterion for the transition of boiling modes was derived based on non-equilibrium thermodynamics, and the self-organized transition processes among different boiling modes were caused by the interactions among active sites or dry patches. Recently (Mosdorf and Shoji, 2004), the pool boiling features in artificial surfaces were further studied, including the nonlinear analysis of surface temperature fluctuation and nucleation sites interaction. Besides the experimental studies, a simple model of heat transfer between the bubbles and heating surface under the nucleation sites was also developed to explain the mechanism of deterministic chaos generation in pool boiling. Two mechanisms of interaction between neighboring nucleation sites were suggested: hydrodynamic one occurring over the heating surface and thermal one occurring inside the heating surface. The interaction between the nucleation sites through the liquid stabilizes the process of bubble growth and departure. The thermal interaction destabilizes the process of bubble growth and departure.

From the point of view of practice, the nonlinear investigation on the flow boiling system is more urgent because the accuracy design, optimum operation and effective control of flow boiling heat exchangers such as the evaporator and nuclear reactor are still quite difficult due to the complexity of the flow boiling phenomena. The nonlinear analysis and numerical simulation were applied to study the instabilities and oscillations appeared in the two-phase flow boiling systems. For the flow boiling system, the physical complexity results from the effects of hydrodynamic, equipment structure and operation modes. Rizwan-unddin and Dorning (1988) reconstructed a chaotic attractor in a periodically forced boiling two-phase flow with single channel system. Clausse and Lahey (1991) unraveled the nonlinear characters from the density wave signals in flow boiling system. Delmastro and Clausse (1994) measured experimentally nonlinear dynamical attractors of a natural circulating boiling flow and found that the complex phenomena of the system exhibit nonlinear features. Kozma et al. (1996) used the fractal technique to characterize the two-phase boiling flow loop in order to develop objective flow regime indicators. It was found that the error of the linear fit of the fractal dimension is a sensitive indicator of the changes in the flow regime, while the fractal dimension value itself is less suitable for flow regime identification and a bi-fractal behavior was found in the measurement temperature signals. Narayanan et al. (1997) studied the phenomena of density wave oscillations in a vertical heated channel by numerical simulation and the complex hydrodynamic behavior like relaxation oscillations, quasi-periodic behavior and chaotic solutions of the two phase flow system in an evaporator by incorporating the effect of a periodic variation in the imposed pressure drop were obtained. Lee and Pan (1999) investigated the dynamics of multiple parallel boiling channel systems with forced flows by numerical simulation. The bifurcations from limit cycle, quasi-periodic to chaotic oscillation were demonstrated for a 3-channel system. Cammarata et al. (2000) carried out the nonlinear analysis of a rectangular national circulation loop. The reconstructed phase maps from the time series of temperature were investigated and the fractal dimensions of attractors were estimated. Their results pointed out the possible existence of chaotic behaviors in the system. Recently, Robert et al. (2004) investigated experimentally the nonlinear dynamics of natural-circulation, boiling two-phase flows and found that the boiling two-phase flow undergoes the well-known Feigenbaum scenario, the period-doubling route toward chaotic behavior.

These nonlinear analyses are valuable for enhancing the physical understanding of such system. The general nonlinear analysis tools such as phase plane map analysis and chaotic invariant estimates were applied most often in these studies. However, as another powerful datum excavating tool, chaotic prediction was utilized little to solve the flow boiling problems. In other words, it may also be valuable to investigate the flow boiling phenomena from the point of view of nonlinear prediction. The chaotic prediction is taken as an effective diagnostic tool to identify chaos from random, and much interesting work on chaotic prediction for some complex systems has been reported in open literature (Farmer and Sidorwich, 1987; George and Robert, 1990; Liu, 1998; Liu and Hu, 2004).

In most chaotic prediction studies, a strict datum comparison in time trajectory between the experiment signal and the prediction signal was emphasized. However, it may also be meaningful to discuss the agreement between the prediction value and the experimental value from the point of view of macroscopic or general characters. In other words, if the agreement between the global parameters estimated from the measuring signal and from the prediction signal or the results analyzed from the measuring signal and from the prediction signal is good, the hydrodynamics of the two systems are considered to be equal and the forecasting is considered to be successful. In order to characterize the general behavior, the time-averaged statistics characteristics, such as the average value, average deviation and standard deviation, power spectrum and chaotic invariants including the correlation dimension and Kolmogorov entropy are used. Similarly, few such studies can be found in open literature (Li et al., 2003).

In this work, the complex behavior of the time series of heat transfer film coefficient in an evaporator with a natural circulating two-phase boiling flow was investigated from the point of view of generally chaotic prediction to unravel the motion mechanism and to find a simple nonlinear model to forecast the heat transfer behavior. The chaotic forecasting

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