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Control of density wave oscillations in boiling channel☆

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HIGHLIGHTS

- Numerical studies on the uncontrolled dynamics and the controlled dynamics of boiling flow in the mini-channel.
- Quasi-periodic bifurcation of periodic orbits.
- Performance of NMPC for controlling the oscillations.

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ABSTRACT

The present study reports uncontrolled behavior and controlled behavior of boiling flow in a mini-channel excited by step perturbation and periodic perturbation. It also demonstrates the performance of nonlinear model predictive control (NMPC) in reducing the chaotic oscillations. The control performance significantly varies when the control region is changed from the supercritical bifurcation (stable periodic orbit) region at high inlet subcooling to the subcritical bifurcation (unstable periodic orbit) region at low inlet subcooling. The study also includes the effect of forcing amplitude and forcing frequency on the uncontrolled and controlled dynamics of the channel.

1. Introduction

Complex chaotic flow oscillations are often encountered as operational instabilities in forced-flow boiling channels for nuclear and chemical applications. The studies on the oscillations have immense academic interests as well. One of the major types of the oscillations reviewed by Kakac and Bon (2008) and Goswami and Paruya (2011) is density wave oscillation (DWO) in which, pressure drop oscillates with mass flow rate in out-of-phase mode. Several complex behaviors of the channel including strange attractors, subcritical and supercritical bifurcations have been identified during DWOs by many investigators (Achard et al., 1985; Rizwan-uddin and Dorning, 1988; Narayanan et al., 1997; Lin et al., 1998; Papini et al., 2012). The control of chaotic oscillations is intended to promote or eliminate it depending on the applications and to stabilize a system on a desired trajectory. Promoting chaos accelerates mixing, heat and mass transport, and chemical reactions. In some applications, the chaos causes mechanical vibrations, fatigue failure of mechanical systems and increased drag in flow systems (Wang et al., 1992). DWOs, pressure-drop oscillations, thermal oscillations and flow-regime oscillations in the forced-flow boiling channel can lead to such severe consequences.

Control of these complex oscillations is, therefore, another major concern. Perturbation techniques viz., OGY method (Ott et al., 1990), active (feedback) control technique (Pyragas, 1992) and optimal control strategy (Yuen and Bau, 1999) including nonlinear model predictive control (NMPC) are being used to control chaotic oscillations in a fluid convection loop. The essence of the OGY method is to apply a small judiciously chosen perturbation of a control parameter in order to stabilize such periodic dynamics (which would be, in fact, unstable for the unperturbed system). This perturbation is chosen based on the reconstruction of the locally linearized dynamics around a desired trajectory. The method relies on time-delay embedding. Thus, it can be used in the experimental studies where the knowledge of the system dynamics is unavailable. The main disadvantage of this method is its dependency on the time of filling the chaotic attractor by trajectories. On the other hand, the active control strategy designs a proper feedback line, introducing a perturbation of a state variable in a process. The method requires the experimental time series of the state variable. A negative feedback line

Abbreviations: DWO, density wave oscillation; NMPC, nonlinear model predictive controller; SD, standard deviations

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can be designed to be a proportion to the distance between the actual value of the state variable, and the value delayed by a time lag. Although these two methods have been used successfully in very complex systems like Rayleigh–Bénard convection, thermal convection loop, etc., they do not necessarily follow the optimal path and always suffer from appreciable uncertainties. The issues of the best possible performance of the chaos control scheme remain open.

The optimal control strategy for the chaos control in a thermal convection loop (single-phase liquid) was proposed during the late 1990s (Yuen and Bau, 1999; Bewley, 1999). Bewley et al. (2001) proposed the use of direct numerical simulations (DNS) in MPC to quantify the best possible system performance in controlling flow actuations and derive the optimized control correlations with the near-wall coherent structures that dominate the process of turbulence production in wall-bounded flows. Murshed et al. (2003) have shown that NMPC performance in terms of stabilizing time and control action is better than that of the other controllers. It gives a better result using Lyapunov stability criterion than the other control strategies in terms of stabilizing time and movement rate of the controller. The NMPC stabilizes the system very quickly, as they observed, but gives many spikes in the control action if noise is present. Zhang et al. (2011) successfully solved flow maldistribution problem in parallel boiling channels based on MPC and gave a proposal of reducing DWOs in a forced-flow boiling channel. Maddala and Rengaswamy (2013) demonstrated the possible applications of active control strategy based on MPC in droplet microfluidics and observed that a variety of digital signals (step, pulse, impulse and sinusoids) based on the relative exit distance can be generated through an appropriate choice of MPC-objective function.

Motivated by the robust performance of NMPC in controlling the flow oscillations, we extend the study of Paruya et al. (2012) on a mini-boiling channel to integrate NMPC with the channel for controlling DWOs at its reference trajectory. Periodic forcing of the pressure drop on the boiling channel, studied by the researchers (Rizwan-uddin and Dorning, 1988; Narayanan et al., 1997; Lin et al., 1998), leads to more chaotically complex attractors. The control of the attractors for safe operation is equally important. The literatures have an appreciable gap in this regard. Particularly, our periodic forcing differs from theirs in that we impose it on the oscillating boiling channel instead of forcing the non-oscillating channel. The problem, in general, is of particular interest in nuclear-coupled channel, cardiac applications and biological systems. We apply NMPC at the marginal stability boundary (MSB) in the parameter space of inlet subcooling and channel power to experience its performance in the subcritical region and in the supercritical region. Locally linearized model based on the numerically evaluated Jacobian and the original nonlinear model, has been employed to calculate the bias for minimizing the mismatch. The time series of the controlled variable obtained from the numerical simulations has been analyzed to identify the structural nature of the flow oscillations based on the evaluation of power spectral density (PSD) using fast Fourier transform (FFT) (Parker and Chua, 1989) and the evaluation of Lyapunov exponent computed using the method of Rosenstein et al. (1993).

2. Nonlinear analysis of DWOs

The schematic of the heated boiling channel under consideration is presented in Fig. 1. Three-equation homogeneous equilibrium model (HEM), and moving nodal scheme (MNS) have been exercised to compute the two-phase flow dynamics. The model consists of the conservation equations for mass, energy and momentum of two-phase steam–water system. In this formulation, the steam–water

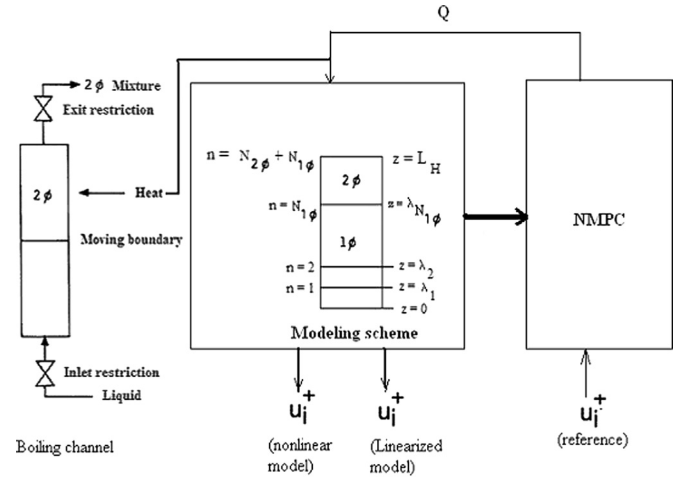

Fig. 1. Schematic of NMPC of boiling channel with nodalization.

flow is assumed to be homogeneous (the velocities of the steam phase and the water phase are same). In the recent past, authors (Achard et al., 1985; Narayanan et al., 1997; Lin et al., 1998; Paruya et al., 2012) have used HEM to study the bifurcations in DWOs. In most of the studies, there is no clear explanation on the use of HEM. Van Bragt et al. (2002) recommended HEM for modeling boiling loop at low power and low pressure. The conditions of low power and low pressure also apply to our investigations in which Q is below 1.5 kW and p is 2.0 atm. At low power and low pres, vapor phase becomes saturated and does not get superheated while the steam quality and void fraction become very less. Consequently, the phases remain at the state of equilibrium. The velocity becomes very low for the low bouncy force due to the formation of small bubbles. So, the velocity of vapor phase and liquid phase remains almost same. Particularly, at low pressure, the boiling is initiated with low power as the temperature of boiling and the required wall superheating are low. However, the results obtained with HEM model have already been validated by Paruya et al. (2012) with the experimental data of Saha (1974) for MSB. A good agreement between the predicted instability thresholds and experimental instability thresholds is observed in high inlet subcooling number (N_{sub}) region that validates the assumption of homogeneous flow in high N_{sub} (low steam quality). At low N_{sub}, the predictions become slightly conservative and the modeled boiling system becomes less stable compared to the experimental one. The numerical results were also compared with the numerical results of Rizwan-uddin and Dorning (1988) and Narayanan et al. (1997) (in Paruya et al., 2012). The frequencies of oscillations showed a good agreement.

The balance equations for the mixture are transformed to the dimensionless form, which is shown in the following equations. The dimensionless quantities and the other symbols have been defined in the Nomenclature section.

Dimensionless mixture mass equation:

$$\frac{\partial \rho^+}{\partial t^+}+\frac{\partial(\rho^+ u^+)}{\partial z^+}=0 \quad (1)$$

Dimensionless mixture momentum equation:

$$\frac{\partial(\rho^+ u^+)}{\partial t^+}+\frac{\partial(\rho^+ u^{+2})}{\partial z^+}=-\frac{\partial p^+}{\partial z^+}-\Lambda\rho^+ u^{+2}-\frac{1}{2}\sum_{j=1}^{N} k_j\rho_j^+ u_j^{+2}-\frac{\rho^+}{\mathrm{Fr}} \quad (2)$$

Dimensionless mixture energy equation:

$$\frac{\partial \rho^+ h^+}{\partial t^+}+\frac{\partial(\rho^+ h^+ u^+)}{\partial z^+}=1 \quad (3)$$

In order to derive the moving boundary formulation, we use the above dimensionless forms (Eqs. (1)–(3)). The dimensionless form