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Modeling and parametric analysis of two-phase fluid stability in boiling process in a thermal channel

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ABSTRACT: In this paper, analysis of two-phase flow instability in a boiling process is investigated and a simple and comprehensive model is modified to express pressure drop. The defined model and nondimensional numbers give a comprehensive sight of different parameters' effect on the oscillations. By using Lyapunov stability analysis, conditions in which instability occurs are identified. The effect of parameters on the diagram of pressure drop versus mass flow rate are investigated and the existence of extremum is discussed. The oscillation form varies according to the value of the basic oscillation damping parameter from an elliptical orbit to a quadrilateral, corresponding to the pressure drop curve. The characteristics of their oscillation circuit, amplitude, and frequency were discussed analytically in terms of problem quantities. In addition, by nonlinear analysis, variation of the oscillation period is examined and its relation to the parameter of systems is investigated. In high operating pressure, the oscillation period is a function of fluid density and geometry of the thermal channel. Also for high compressible volumes, this characteristic increases with decreasing input mass flow rate in an unstable condition

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1- Introduction

To reduce equipment volume and control temperature in high capacity heat transfer in industrial processes, two-phase flow is greatly used. In many industries such as boiling water reactors, steam boilers, evaporators and air conditioning equipment heat transfer to operating fluid causes phase change. This phase change affects the thermo-hydraulic of flow and can lead to undesirable instabilities. The purpose of the studies in this field is to investigate the design, operation, and safety issues of equipment used in various industries [1-3]. The instability of pressure drop oscillations is a compound dynamic instability and it triggers with a static instability (flow excursion). The main feature of this instability is the low frequency and high amplitude [4, 5].

Padki et al. [6], by analyzing nonlinear dynamics and bifurcation theory, stated that the instability of pressure drop fluctuations occurs after the supercritical point of the Hopf bifurcation, which corresponds to the onset of the negative slope of the characteristic curve. In this study, the equations mass velocity at the operation point have been used as characteristic parameter. Rahman and Singh [7] performed nonlinear instability analysis to investigate PDO. The Hopf bifurcation for the supercritical and subcritical state has been studied and it has been shown that by examining the large perturbations, the instability of pressure drop oscillations also occurs for the states showing linear instability stable.

In this paper, by introducing appropriate dimensionless characteristic quantities, it is possible to investigate the shape of the characteristic curve of the pressure drop. Also, the role of different parameters on the amplitude and period of oscillations is specified.

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2- Theory and Modelling

Fig. 1 shows a horizontal boiling channel in which subcooled liquid is heated up until evaporates at the boiling boundary. The continuity and energy equations for each of the two zones are written separately, while the momentum equation is expressed for the whole heated channel. A thermodynamic equilibrium between phases, two-phase homogenous model, and be one-dimensional flow is assumed.

The governing equations can be described in the dimensionless form:

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

$$\frac{\partial G}{\partial t}+\frac{\partial}{\partial z}\left(\frac{G^2}{\rho}\right)=-\frac{\partial P}{\partial z}-N_f\frac{G^2}{\rho} \quad (2)$$

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial z}(Gh)=\Phi \quad (3)$$

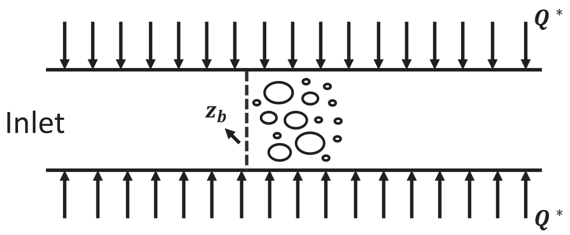

Fig. 1. Schematic view of the heating channel

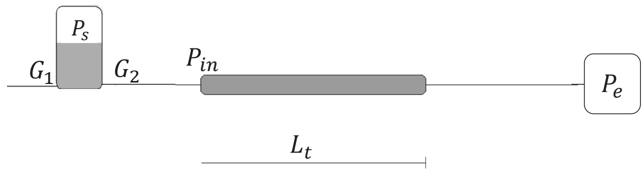

Fig. 2. A simple schematic view of a boiling channel

In order to obtain the basic solution for dynamic analysis, the first step is to analyze the steady-state condition in the pipe as normal. In the steady-state condition, the continuum equation leads to a constant mass velocity (G). Also by considering z_b as the boiling start length, the energy equation will be simplified to the following equation.

$$z_b = G \tag{4}$$

Fig. 2 shows a schematic diagram of the problem, which is the simplest system to investigate the instability of PDO.

If m_0^* and m^* represent the mass flow rate of the surge tank inlet and outlet, P_0^* the outlet pressure, and P^* the pressure inside the surge tank, the mass and momentum equation can be rewritten as follows:

$$\frac{dm^*}{dt^*} = \frac{A^*}{L_t^*}\left(P^* - P_0^* - \Delta P^*\right) \tag{5}$$

$$\frac{dP^*}{dt^*} = \frac{P^{*2}}{P_t^* P_0^* V_t^*}\left(m_0^* - m^*\right) \tag{6}$$

Considering the steady-state conditions as the basic solution and adding the perturbation values ε_G to the mass velocity and ε_P to the pressure in the above equations, linear analysis is performed regardless of the high-order terms.

To solve the nonlinear equations system, a method based on the residual weighted method is used. Since the equations are nonlinear, the equations are linearized in the first step in terms of the predicted initial values. The predicted values for this purpose are obtained by solving the equation using the mono implicit Range Kutta method. This method has been reduced computational cost and controlled instability induced by errors [8].

3- Results and Discussion

According to Fig. 3, the steps of the Oscillations can be considered as follows.

a- Increasing the pressure in the surge tank (I-II).

b- flow excursion from two-phase to liquid state (II-III).

c- Reducing the pressure in Bump Tank (III-IV).

d- Flow excursion from low quality to high-quality steam (IV-I).

Critical points for the dynamical system are the points () and (). To investigate the potential of instability, fuzzy plates can be investigated for points set at and . Fig. 4 shows the fuzzy portraits of these points for the sample mode. As can be seen in the figure, the fuzzy portrait for the critical point is of the center type and shows the instability potential. From a point adjacent to this point, the instability of the system begins with the observation of the fuzzy node in fuzzy portrait. This instability continues until the neighborhood for Fig. 4(a). However, for Fig. 4(b), the instability table near the corresponding point will end.

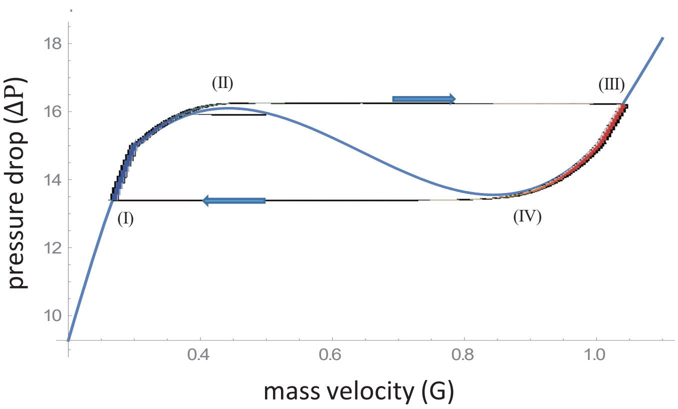

Fig. 3. Limit cycle circuit

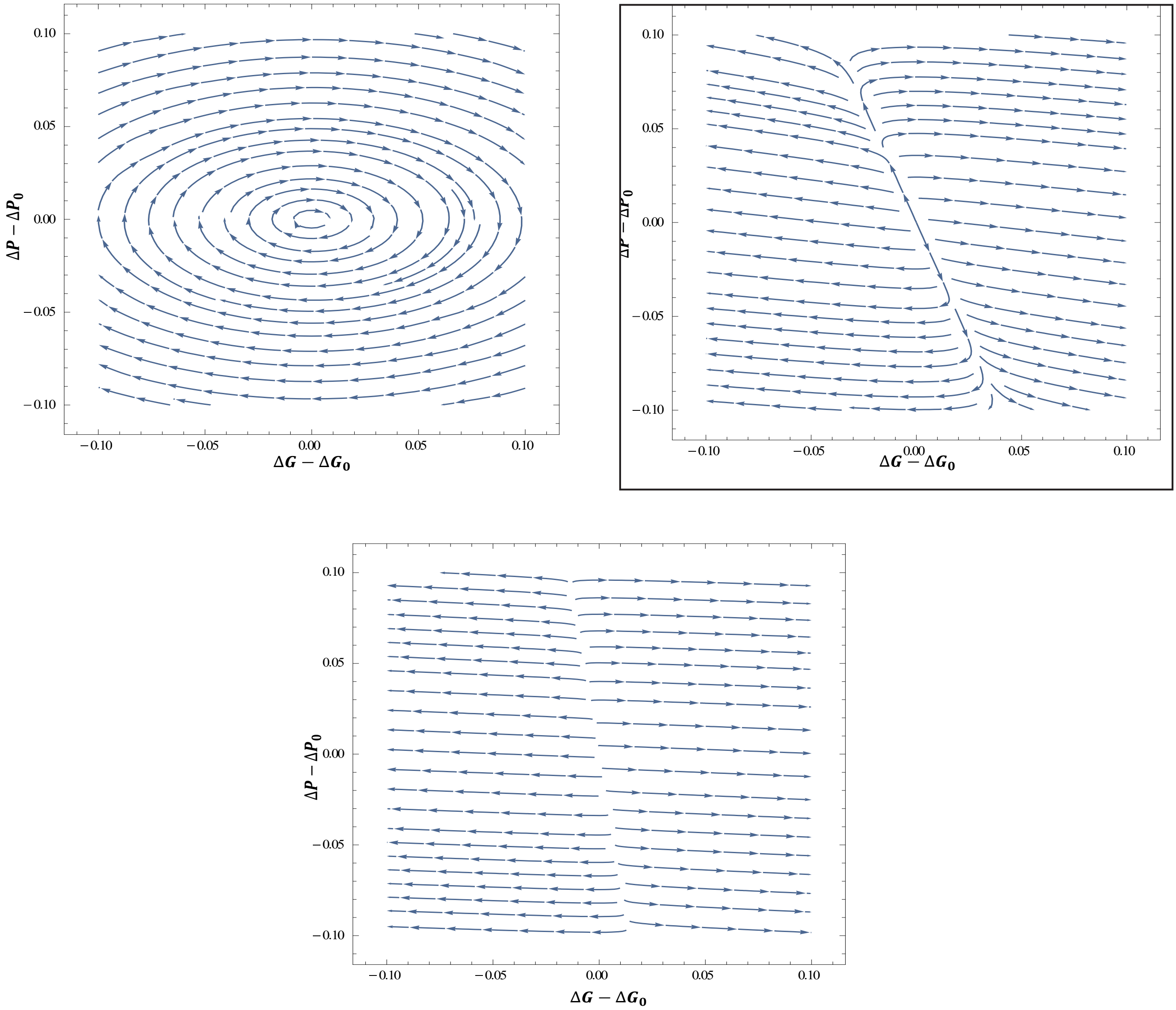

Fig. 4. Phase portrait for F^' (G)<0 and a) G=G_1, b) G~G_1, c) G_1<G<G_2

4- Conclusions

In this paper, by using a new analytical model, an analysis of pressure drop oscillations in a boiling channel is performed. Using an integrated equation system and introducing characteristic quantities, the relationship of pressure drop under steady-state conditions was obtained in terms of mass velocity.

The dimensionless form introduced in this paper in terms of the introduced characteristic quantities shows that the two defined variables, reaction frequency and the frictional loss factor, are directly effective in the shape of the curve and the instability region. The period and amplitude of the oscillations increase with decreasing mass flow velocity at the starting operating point in the negative slope.

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