Analysis of Density Wave Oscillations in a Boiling Channel by a New Analytical Model

M. R. Shahnazari [1*], A. Amjadigolpayegani [2], A. Saberi [2]

[1a] Associate Professor, Department of Mech. Eng., K. N. Toosi University of Technology
[2]Ph.D. Student, Department of Mech. Eng., K. N. Toosi University of Technology

ABSTRACT

Two-phase flow instabilities are observed in many areas of industrial applications such as turbomachinery, refrigeration systems, water boiling reactors and similar systems. Predicting fluid flow parameters such as pressure drop, stability region during boiling and oscillation characteristics are the determining factors in the design of two-phase flow equipment. In this paper, density wave oscillations type instability in boiling process is analyzed. By introducing appropriate dimensionless variables, an integrated model for the process is presented. The model is solved for steady state response of the system by using numerical analysis of a developed numerical method based on weighted residual method. Stability region is determined in reaction frequency versus ratio of reaction frequency to inlet mass flow plane. In addition, friction number effect on stability threshold is assessed. The effect of mass flow rate, inlet subcooling, system pressure and other important process parameters on the oscillation characteristics as well as the instability boundary are investigated. The results show that with increasing mass flow, the system becomes more stable for density wave oscillations occurrence. The critical quality of the exhaust vapor also decreases with increasing mass flow. On the other hand, the period of oscillations and its amplitude increases with increasing mass flow.

KEYWORDS

Two phase flow, Instability, Density wave oscillations, Boiling, Nonlinear Dynamic

1. Introduction

In order 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 thermohydraulic of flow and can lead to undesirable instabilities [1-3].

Wallis et al .'s article is the first in a series of studies on two-phase flow systems [4]. The analytical works has mainly focused on finding the sustainability limit, which includes much of the early research. Numerical studies have mainly attempted to estimate instabilities along the amplitude and period of oscillations. Ishi et al. Extended the formulation of the analysis and proposed important similarity groups for two-phase systems, including numbers, phase change, subcooling, Froude, and Reynolds number [5]. Flow stability maps are thus obtained on the subcooling number diagram in terms of phase change number. In recent years, the study of flow in small channels has also been considered, with most results consistent with classic results [6]. In a different work using the high speed camera and investigating the motion of high-density and low-density fronts, O'Neill et. al. have identified the instability of density wave oscillations [7].

In this paper, for pressure drop variations in terms of mass velocity, a close and analytical answer has been presented. The stability region and the effect of the parameters are analyzed. The variation of the density wave oscillations, their amplitude and their period are also discussed.

2. Theory and Modelling

Fig. 1 shows a horizontal boiling channel in which subcooled liquid is heated up until evaporates at 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 pressure drop of the channel is held constant.

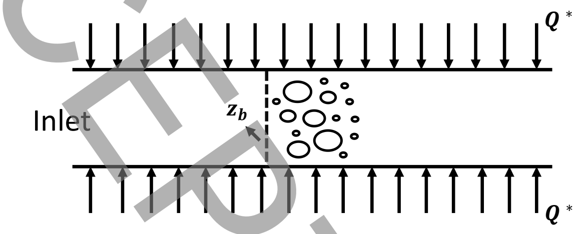

Fig. 1. Schematic representation of the problem

Governing equation can be described in dimensionless form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial G}{\partial z}=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial z}(Gh)=1 \tag{2}$$

$$\int_0^1 \frac{\partial G(z,t)}{\partial t}dz=\Delta P_{tot}-\Delta P(t) \tag{3}$$

Homogenous density and reaction frequency can be expressed as:

$$\rho_H=\frac{1}{1+xv_{fg}} \tag{4}$$

$$\Omega=\frac{v_{fg}}{h_{fg}} \tag{5}$$

In order to solve the equation 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 modified implicit Range Kutta method. This method has been reduced computational cost and controlled instability induced by errors [8].

3. Result and Discussion

Fig. 2 depicts pressure drop characteristic curve for R134a by assuming averaged friction number for whole channel.

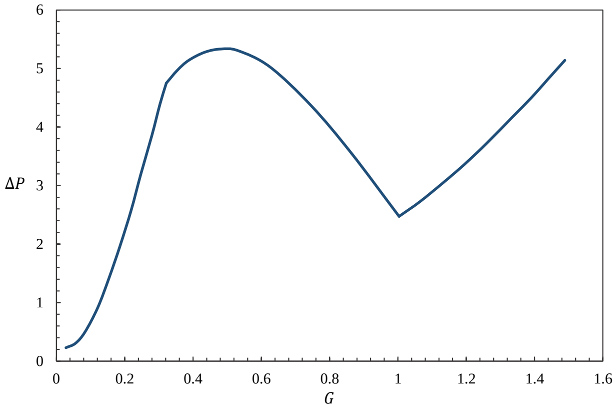

Fig. 2. Pressure drop characteristic curve in term of mass velocity

Also, in Figs. 3 to 5 mass velocity oscillations are demonstrated for converged oscillations, limit cycle oscillations and diverged oscillations respectively. Exit vapor quality and boiling boundary is also shown in Fig. 5.

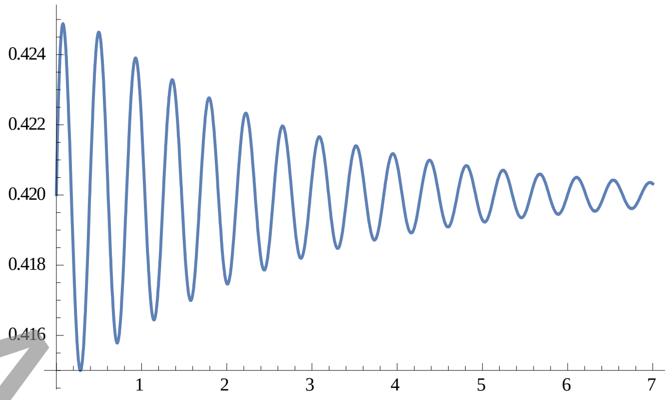

Fig. 3. Converged oscillations mass velocity oscillations

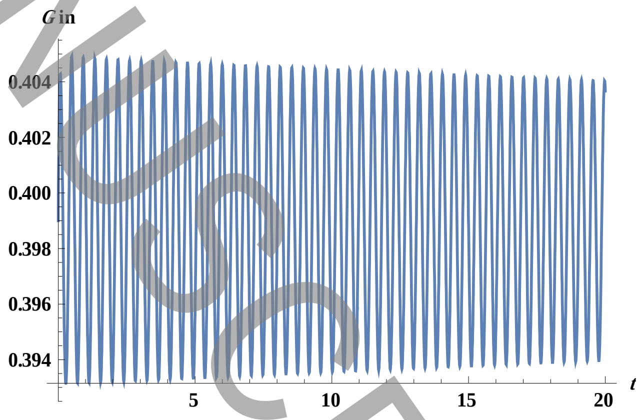

Fig. 4. Limit cycle mass velocity oscillations

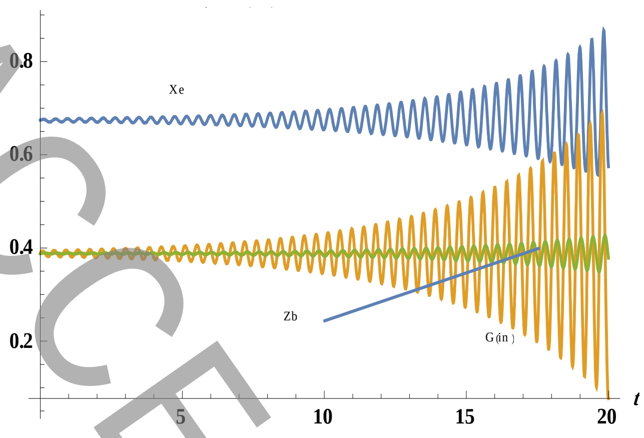

Fig. 5. Diverged oscillations mass velocity, exit vapor quality and boiling boundary

As the boundary conditions approach instability point, mass velocity begins to oscillate, due to the difference of propagation speed between single-phase and two-phase region. Any change in flow or volume fraction in the two-phase region results in a change in pressure drop. As the disturbance propagates slowly over the two-phase region, a significant delay in the onset of the disturbances in the two-phase region will occur and oscillations are started. These oscillations decrease and the system again stabilizes after a certain time (Fig. 3). These oscillations turn into limit cycle oscillations as they approach the instability region (Fig. 4) and eventually diverge (Fig. 5).

Fluid residence time in the heated channel has been used as a characteristic time to investigate the period of oscillation. As shown in Fig. 6, Variation of period to time residence of fluid ratio versus reaction frequency is plotted. Although oscillation period increases with increasing Ω, for $\Omega > 10$ this increasing rate declines.

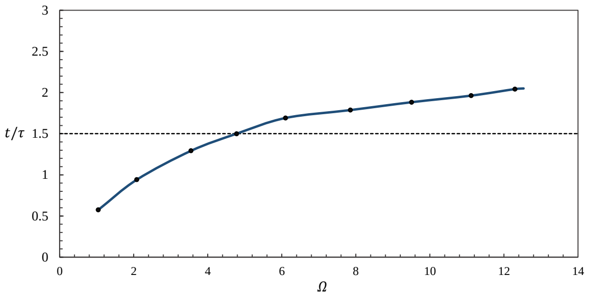

Fig. 6. Variation of period to time residence of fluid ratio versus reaction frequency

4. Conclusions

In this paper, by using a new analytical model, analysis of density wave oscillations in a boiling channel is performed. By integrating the equations in the steady state, an analytical relationship is found between pressure drop and mass velocity. In addition, the nonlinear equations are generally solved. This solution specifies the possibility of checking oscillations in terms of input parameters and quantities. In other words, the proposed model allows the linear analysis of density wave instability over a wide range of parameter changes for different fluids.

The system pressure does not have a significant effect on the period of DWO, however, with increasing pressure, the amplitude of the oscillations slightly decreases and the period of the oscillations increases.

The period of the oscillations is approximately twice that of the fluid residence time in the channel, although it decreases with decreasing subcooling value and tends to be less than 1/2 for low subcooling values.

5. References

[1] L.C. Ruspini, C.P. Marcel, A. Clausse, Two-phase flow instabilities: A review, International Journal of Heat and Mass Transfer, 71(0) (2014) 521-548.
[2] L. Tadrist, Review on two-phase flow instabilities in narrow spaces, International Journal of Heat and Fluid Flow, 28(1) (2007) 54-62.
[3] J.A. Boure, A.E. Bergles, L.S. Tong, Review of two-phase flow instability, Nuclear Engineering and Design, 25(2) (1973) 165-192.
[4] G.B. Wallis, J.H. Heasley, Oscillations in Two-Phase Flow Systems, Journal of Heat Transfer, 83(3) (1961) 363-369.
[5] S. Kakaç, L. Cao, Analysis of convective two-phase flow instabilities in vertical and horizontal in-tube boiling systems, International Journal of Heat and Mass Transfer, 52(17) (2009) 3984-3993.
[6] L. Chen, P. Zhou, R. Huang, X. Han, S. Hua, Z. Li, L. Gao, Experimental investigation on the suppression factor in subcooled boiling flow, Applied Thermal Engineering, 135 (2018) 549-558.
[7] L.E. O'Neill, I. Mudawar, M.M. Hasan, H.K. Nahra, R. Balasubramaniam, J.R. Mackey, Experimental investigation of frequency and amplitude of density wave oscillations in vertical upflow boiling, International Journal of Heat and Mass Transfer, 125 (2018) 1240-1263.
[8] P. Muir, M. Adams, Mono-implicit Runge–Kutta–Nyström methods for boundary value ordinary differential equations, Tech. Report 03–2000, Dept. Math. and Comp. Sci., Saint Mary's University …, 2000.