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NUMERICAL MODELING OF THE DYNAMIC OF PARALLEL BOILING CHANNELS SYSTEMS

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RESUMEN

Se presenta un análisis no lineal del comportamiento dinámico de dos canales paralelos acoplados utilizando un modelo de parámetros concentrados. El modelo se basa en una aproximación de Galerkin para las ecuaciones de conservación de un canal en ebullición, utilizando perfiles lineales de entalpía. Se encontraron interesantes resultados, incluyendo oscilaciones en fase y en contrafase de los parámetros termohidráulicos tales como el caudal de entrada y la posición de la frontera de ebullición. Éstos resultados son mostrados en diferentes proyecciones del espacio de las fases, utilizando elementos de la teoría moderna de sistemas dinámicos.

ABSTRACT

A non-linear analysis of the dynamic behavior of two coupled parallel channels using a lumped parameter model is presented. The model is based on a Galerkin approximation of the conservation equations for a boiling channel, which assumes linear enthalpy profiles. Interesting results, including in-phase and out-of-phase oscillations of the thermalhydraulic parameters such as inlet flow rates and boiling boundaries positions, have been found. These results are shown in different phase-space projections using elements of the modern theory of dynamic systems.

INTRODUCTION

The use of boiling heated channels is very common in many important industrial applications, such as, boiling water nuclear reactors, steam generators, various chemical processes, cryogenic systems, etc. Under certain operating conditions the dynamic behavior of these systems become unstable due to lags in the phasing of pressure-drop feedback mechanisms, been the most common manifestation self-excited oscillations of the flow variables. The study of the non-linear behavior of boiling flow systems is therefore very important in order to improve efficiency and set safety limits.

The dynamic behavior of boiling channels have been analyzed in the past by numerous investigators. Consequently this phenomenon is rather well understood in single channels and in boiling loops.

In contrast, the understanding of the non-linear behavior in coupled parallel channels is rather incomplete.

In the present paper a non-linear analysis of the dynamic behavior of two coupled parallel channels using a lumped parameter model is presented. The model is based on a Galerkin nodal approximation of the conservation equations for a boiling channel. Interesting results, including in-phase and out-of-phase oscillations of the thermalhydraulic parameters such as inlet flow rates and boiling boundaries positions, have been found. These results are analyzed using the modern theory of dynamic systems showing different projections in the phase-space.

BOILING SYSTEM MODEL

An improved version of the single channel finite-elements model presented by Clausse et al. [1,2,3] in its dimensionless form is used to analized the system of parallel heated channels shown in Figure 1.

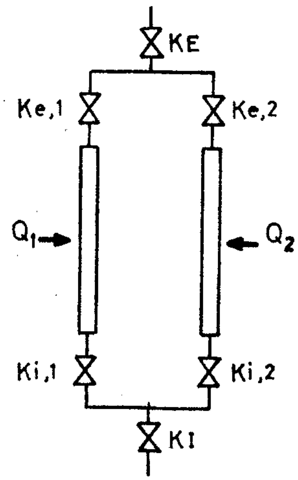

Figure 1: Schematic diagram of the parallel heated channel system

Single-phase Region

The single phase region of each channel is subdivided into N_s nodes of variable length. The enthalpy increase from the inlet, h_i, to saturation, h_f, is divided into N_s equal intervals. Therefore, the boundary, L_n, between subcooled nodes n and $(n+1)$ is defined as the point where the fluid enthalpy is:

$$h_n = h_i + \frac{n}{N_s}(h_f - h_i) \tag{1}$$

The differential equations governing the dynamics of the enthalpy boundary L_n can be derived using a Galerkin technique [4], and assuming a linear enthalpy profile, giving:

$$\frac{dL_{n,j}}{dt} = 2u_{i,j} + 2N_s Q_j (L_{n,j} - L_{n-1,j}) - \frac{dL_{n-1,j}}{dt} \tag{2}$$

where j stands for the j-channel and Q_j is the ratio between j-channel power to the average power.

Two-phase Region

The masses of the fluid in each heated channel ($M_{ch,j}$) have been chossen as a state variables. They correspondent conservation equations can be derived by integrating the continuity equation over each channel length, which gives:

$$\frac{dM_{ch,j}}{dt} = u_{i,j} - \rho_{e,j}u_{e,j} \tag{3}$$

The velocity at the exit of each channel ($u_{e,j}$) can be calculated combining the mass and energy conservation equations and the equation of state, giving:

$$u_{e,j} = u_{i,j} + N_{sub}Q_j(1 - L_{N,j}) \tag{4}$$

where N_{sub} is the subcooling number [5].

The exit density of each cahnnel ($\rho_{e,j}$) can be expressed in terms of the heated channel masses by assuming a linear enthalpy profile inside the two-phase regions:

$$M_{ch,j} = L_{N,j} + (1 - L_{N,j})\frac{\ln(1/\rho_{e,j})}{(1/\rho_{e,j} - 1)} \tag{5}$$

To reduce integration time a polinomial fit of Eq. (5) was used to relate $\rho_{e,j}$ with $(M_{ch,j} - L_{N,j})/(1 - L_{N,j})$.

Clossure of the Model

The model is closed by imposing the external pressure drop boundary conditions on the inlet valve, boiling channel and exit valve. Integrating the momentum equation along the channel and taking into count the losses in the inlet and exit valves we have:

$$\begin{aligned} Eu\Delta P_{ext} = {} & K_I\left(\frac{u_{i,1} + u_{i,2}}{A_I}\right)^2 \\ & + K_B\left(\frac{u_{e,1} + u_{e,2}}{A_B}\right)\left(\frac{\rho_{e,1}u_{e,1} + \rho_{e,2}u_{e,2}}{A_B}\right) \\ & + \Delta P_{In,j} + \Delta P_{G,j} + \Delta P_{fr,j} + \Delta P_{a,j} \end{aligned} \tag{6}$$

where A_I and A_B are the inlet and exit area refered to the channel area.

The pressures drops due to inertia, gravity, friction and aceleration in each channel can be expressed as:

$$\Delta P_{In,j} = \frac{d}{dt}\left(M_{ch,j}u_{i,j} + N_{sub}Q_j\frac{(1 - L_{n,j})(1 - M_{ch,j})}{(1/\rho_{e,j} - 1)}\right) \tag{7}$$

$$\Delta P_{G,j} = \frac{M_{ch,j}}{Fr} \tag{8}$$

$$\begin{aligned} \Delta P_{fr,j} = {} & \Lambda_{1,j}L_{N,j}{u_{i,j}}^2 + \Lambda_{2,j}\Big[(M_{ch,j} - L_{N,j}){u_{i,j}}^2 \\ & + 2N_{sub}Q_j\frac{u_{i,j}(1 - L_{N,j})(1 - M_{ch,j})}{(1/\rho_{e,j} - 1)} \\ & + \left(\frac{N_{sub}Q_j(1 - L_{N,j})}{(1/\rho_{e,j} - 1)}\right)^2\left(\frac{(1/\rho_{e,j} - 3)(1 - L_{N,j})}{2}\right. \\ & \left. + M_{ch,j} - L_{N,j}\right)\Big] + K_{i,j}u_{i,j}^2 + K_{e,j}\rho_{e,j}u_{e,j}^2 \end{aligned} \tag{9}$$

$$\Delta P_{a,j} = \rho_{e,j} u_{e,j}^2 - u_{i,j}^2 \tag{10}$$

where Fr is the Froude number and Λ_1 and Λ_2 are the single and two-phase distributed friction coefficients.

RESULTS

The system of parallel channels is described using $2N_s + 4$ ordinary differential equations. This system of equations was numerically integrated by means of a Runge-Kutta method [6].

For two identical channels, two kinds of oscillatory behavior were found depending on the values of the valves loss coefficients. This result was observed in experiments reported elsewhere [7].

In a case where the equivalent averaged channel [8] is more unstable than each channel separatly, in-phase density-wave oscillations were observed. Figure 2 shows a phase-space projections of the limit cycle, where the inlet velocity in one channel is plotted as a function of that of the other one. As we can see the two channels oscillate in-phase.

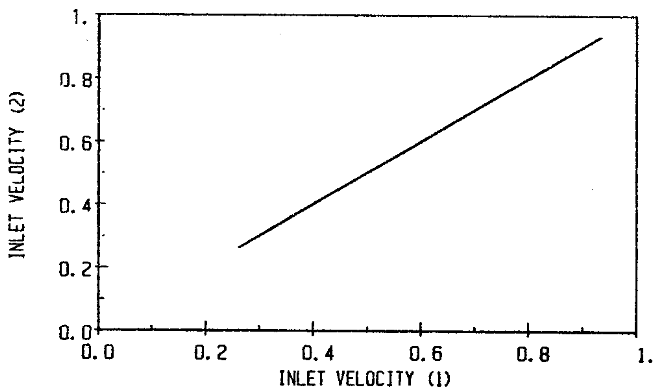

Figure 2: Phase-space projection (in-phase)

In cases where each channel alone is more unstable than the whole averaged system, out-of-phase oscillations where observed. Figures 3 shows the phase-space projection of the limit cycle in this case. It can be seen that the oscillations are not compleatly in counter-phase, which is a consequence of the non-linear coupling.

A system of two different channels was also analysed. Figure 4 shows the phase-space projections of the limit cycle, where the inlet velocity in one channel is plotted as a function of that of the other one, for a system with a power input unbalance. Figure 5 shows the limit cycles described by each channel in the $u_i - \lambda$ plane. It is interesting to see the evolution of the channel masses, shown in Figure 6.

Finally, a system with frictions unbalance was studied. Figures 7 and 8 shows the phase-space trajectories of the limit cycles.

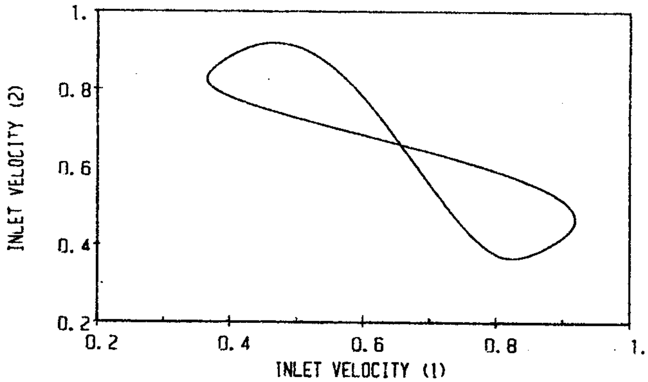

Figure 3: Phase-space projection (out-of-phase)

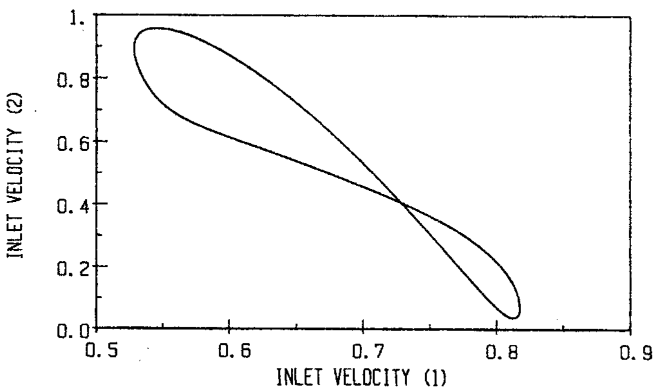

Figure 4: Phase-space projection (power unbalance)

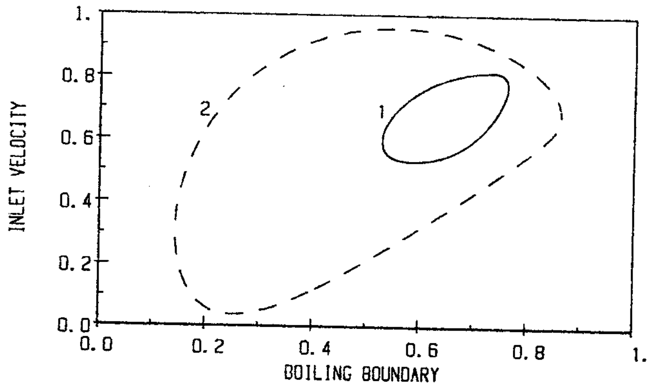

Figure 5: Phase-space projection (power unbalance)

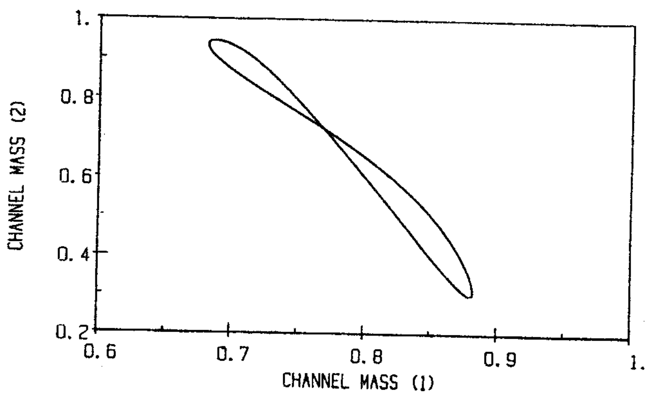

Figure 6: Phase-space projection (power unbalance)

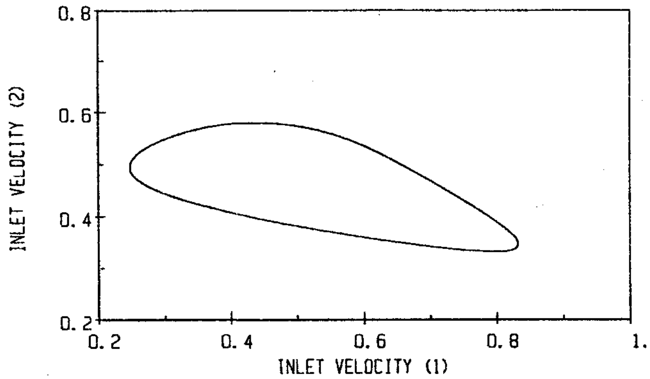

Figure 7: Phase-space projection (friction unbalance)

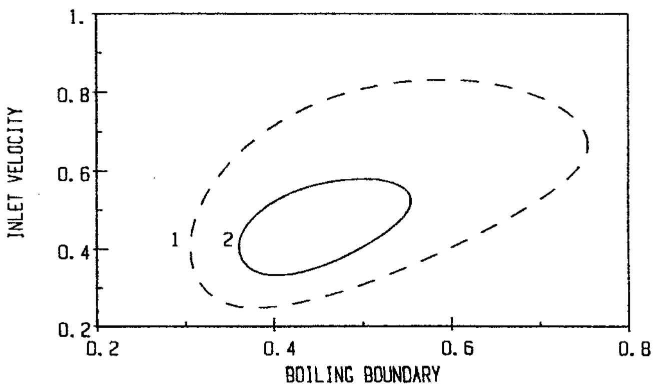

Figure 8: Phase-space projection (friction unbalance)

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