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MODEL PREDICTIONS OF DYNAMIC INSTABILITY THRESHOLD FOR BOILING FLOW SYSTEMS

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Introduction

Boiling flow systems such as boiling water nuclear reactors and once-through steam generators may be susceptible to dynamic instabilities of various types. The most common among these is a low frequency (0.1 - 2 Hz, typically) oscillatory flow instability of the limit-cycle type termed 'density-wave oscillations (DWO)'[1].

In the present paper, two different computer models have been used to predict the DWO threshold power input for various operating conditions of an experimental system[2] which features an electrically-heated test section assembly and water as the experimental fluid. One of the models [3,4], a frequency-domain model, has been in use for quite some time in the nuclear industry. The other is an improved version of a time-domain two-fluid model proposed by us recently[5].

The Models

(I) The time-domain two-fluid model

The time- and cross-sectionally- averaged equations (written per unit mixture volume) for phase k (k = G for vapor, k = L for liquid) are:

<u>Mass</u>

$$\frac{\partial}{\partial t}[\langle\alpha_k\rangle_2\bar{\bar{\rho}}_k] + \frac{\partial}{\partial z}[\langle\alpha_k\rangle_2\bar{\bar{\rho}}_k\langle\bar{\bar{u}}_{kz}\rangle_2] = \langle\Gamma_k\rangle_2 \qquad (1)$$

<u>z-Momentum</u>

$$\frac{\partial}{\partial t}[\langle\alpha_k\rangle_2\bar{\bar{\rho}}_k\langle\bar{\bar{u}}_{kz}\rangle_2] + \frac{\partial}{\partial z}[C_k\langle\alpha_k\rangle_2\bar{\bar{\rho}}_k\langle\bar{\bar{u}}_{kz}\rangle_2{}^2]$$

$$= - \langle\alpha_k\rangle_2 \frac{\partial \bar{\bar{p}}}{\partial z} + \underbrace{\frac{P_w}{A_{x-s}} \langle\alpha_k\rangle_2 \tau_{w,z}}_{\text{(wall friction)}} + g_z \rho_k \langle\alpha_k\rangle_2 + \langle\Gamma_k u_{kI,z}\rangle_2 + \underbrace{F^k_{ID,z}}_{\text{(interfacial drag)}}$$

$$\pm \underbrace{\tilde{\mu} \langle\alpha_d\rangle_2 \langle\alpha_c\rangle_2 \bar{\bar{\rho}}_c \left[\frac{\partial}{\partial t} (\langle\bar{\bar{u}}_{dz}\rangle_2 - \langle\bar{\bar{u}}_{cz}\rangle_2) + \langle\bar{\bar{u}}_{dz}\rangle_2 \cdot \frac{\partial}{\partial z}(\langle\bar{\bar{u}}_{dz}\rangle_2 - \langle\bar{\bar{u}}_{cz}\rangle_2)\right]}_{\text{(added mass effect)}} \quad (2)$$

Internal Energy

$$\frac{\partial}{\partial t} [\langle\alpha_k\rangle_2 \bar{\bar{\rho}}_k \bar{\bar{h}}_k] + \frac{\partial}{\partial z} [\langle\alpha_k\rangle_2 \bar{\bar{\rho}}_k \bar{\bar{h}} \langle\bar{\bar{u}}_{kz}\rangle_2] = \frac{\bar{\bar{q}}''_{wk} P_h}{A_{x-s}} + \langle\alpha_k\rangle_2 \frac{\partial \bar{\bar{p}}}{\partial t}$$

$$+ \langle\bar{\bar{\alpha}}_k\rangle_2 \langle u_{kz}\rangle_2 \frac{\partial \bar{\bar{p}}}{\partial z} + \langle\Gamma_k \bar{\bar{h}}_{kI}\rangle_2 + \underbrace{\left\langle\frac{\bar{\bar{q}}''_{kI}}{L_s}\right\rangle_2}_{\text{(interfacial, G-L, heat transfer rate)}} \quad (3)$$

Heated Channel Wall Energy Equation

$$\rho_w c_{pw} \cdot \frac{dT_w(z)}{dt} = q'''_w(z) - \frac{P_h[h_{fo}(z)\{T_w(z) - T_L(z)\} + h_{ncb}(z)\{T_w(z) - T_{sat}(z)\}]}{A_w} \quad (4)$$

Equations (1) through (4) comprise the nonlinear governing equations for the system. Also provided are the interfacial (G-L) transfer equations for mass, axial momentum, and internal energy. Criteria associated with a flow regime map, various constitutive equations such as for wall friction, interfacial drag, interfacial heat transfer, interfacial area concentration, and wall heat transfer are specified as well.

The nonlinear equation set for the boiling flow system

$$\underline{\underline{M}}(\underline{x})\dot{\underline{x}} = \underline{f}\ (\underline{x},\ \underline{u}) \tag{5}$$

is then obtained by finite-differencing the conservation equations (1) - (4) in space (z) using the donor-cell scheme. Here, $\underline{x}$ is the state vector

$$[\ldots\ldots ;\ T_{w_i},\ p_i,\ h_{G_i},\ h_{G_i},\ h_{L_i},\ \alpha_{G_i},\ u_{Gz_i},\ u_{Lz_i}\ ;\ \ldots\ldots]^T \tag{6}$$

where the subscript i denotes the discrete cell number and $\underline{u}$ is the input vector. The equation set (5) is next linearized around a selected steady state operating point. The system instability threshold is now obtained by calculating the eigenvalues of the state matrix. Eigenvalues with positive real part indicate instability, with the imaginary part (if any) yielding the oscillation frequency. If no imaginary part is present although a positive real part is, the instability is judged to be of the Ledinegg type.

The improvement of the present version of this model when compared to the original one[5] consists essentially of a better description of the moving boundaries in the boiling flow system, for example the net vapor generation location.

(II) The frequency-domain model DYNAM[3,4]

This model is based on a separated, nonequilibrium description of boiling flow. The flow system is subdivided into nonboiling, subcooled boiling, bulk boiling, and superheated vapor regions. In the boiling regions, the mixture mass, axial momentum, and internal energy equations are formulated. A modified Bankoff slip ratio relation is used to relate flow quality and vapor fraction.

The conservation equations are linearized for each finite-difference node and then Laplace transformed. The adjacent nodes are coupled and an open-loop transfer function for the flow system is obtained. Finally, the

Nyquist stability criterion is applied to the open-loop transfer function to determine the instability threshold condition.

Results and Discussion

Table 1 shows comparisons of the predicted DWO threshold power input and oscillation time period for the water experiment system[2]. It can be seen that the two-fluid model, (I), predicts the data well consistently. However the second model, (II), generally underpredicts the threshold power input (sometimes by as much as seventeen percent) although the oscillation time period predictions are quite good. Further calculations indicate that both models exhibit correct trends with respect to changes in system parameters such as inlet throttling, outlet throttling, pressure and frictional pressure drop.

The superior predictive capability of the two-fluid model can be attributed to better descriptions of various on-going physical processes in boiling flow such as interfacial transports of mass, momentum, and internal energy.

TABLE 1

Comparison of DWO Threshold Experimental Data for a Steam-Water System [2] With Two Different Theoretical Model Predictions

Expt. No.	p (Pa)	G (kg/m^2.s)	$T_{L_{in}}$ (K)	K_{inlet}	Expt. Q_{in} (KW)	Expt. τ_{osc} (s)	Present Model Q_{in} (KW)	Present Model τ_{osc} (s)	DYNAM [3,4] Q_{in} (KW)	DYNAM [3,4] τ_{osc} (s)
128-07	4.255×10^6	318.	425.1	250	92.5	6.0	88.5	6.5	77.2	6.3
1008-06	4.255×10^6	298.	417.1	250	86.1	6.5	86.1	7.1	78.8	6.7
1125-33	4.083×10^6	220.	419.1	250	63.6	9.0	62.3	9.2	59.4	8.0
122-05	4.053×10^6	220.	422.1	260	61.9	9.0	62.3	9.0	53.6	8.6

$$K_{inlet} \triangleq \frac{\Delta P_{inlet\ valve}}{\rho u^2}$$

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