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Analysis of the Nonlinear Parallel-Flow Two-Phase Instability in a Liquid Metal Reactor Steam Generator

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1. Introduction

The KALIMER-600 being developed at KAERI employs the once-through helically coiled steam generator. The helically coiled steam generator is compact and efficient for heat transfer, however, it suffers from the two-phase instability. It is well known that the parallel flow instability is one of the main sources of instability among various types of instabilities in a helically coiled S/G. In the present study a simple method for analysis of the parallel-flow two-phase instability in a liquid metal reactor S/G is applied to the analysis of parallel-flow instability experiment conducted at TIT (Tokyo Institute of Technology) in Japan.

2. Analysis

In the present paper the method developed by Aritomi et al. [1] is used for analysis of the parallel-flow two-phase instability. The governing equations are as follows;

(1) Continuity equation;

$$\frac{\partial}{\partial t}\left(\rho_g \alpha\right)+\frac{\partial}{\partial z}\left(\rho_g \alpha u_g\right)=\Gamma_g \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho_l (1-\alpha)\right)+\frac{\partial}{\partial z}\left(\rho_l (1-\alpha) u_l\right)=-\Gamma_g \tag{2}$$

(2) Momentum equations;

$$\frac{\partial}{\partial t}\left(\rho_g \alpha u_g+\rho_l (1-\alpha) u_l\right)+\frac{\partial}{\partial z}\left(\rho_g \alpha\ u_g^2+\rho_l (1-\alpha) u_l^2\right) + \frac{\partial}{\partial z}\left(P\right)+\tau_f+\left(\rho_g \alpha g+\rho_l (1-\alpha) g\right)=0 \tag{3}$$

(3) Energy equation;

$$\frac{\partial}{\partial t}\left(\rho_g \alpha i_g+\rho_l (1-\alpha) i_l\right)+\frac{\partial}{\partial z}\left(\rho_g \alpha\ u_g i_g+\rho_l (1-\alpha) u_l\, i_l\right)=q''' \tag{4}$$

From Eqs.(1)-(3) , we can derive following relations.

$$\Gamma_g=\frac{q'''}{L}=\frac{q''\xi_h}{A_c (i_g-i_l)} \tag{5}$$

$$\frac{\partial}{\partial z}(J)=\Gamma_g \Delta v\ ,\ J=\alpha u_g+(1-\alpha) u_l\ ,\ \Delta v=\frac{\left(\rho_l-\rho_g\right)}{\rho_l \rho_g} \tag{6}$$

The time for passing the preheating region and the boiling boundary is given by

$$\tau_B=\frac{\left(i_l-i_{lin}\right)}{q'''}\rho_l \tag{7}$$

$$z_B(t)=\int_{t-\tau_B}^{t} u_{in}(\tau)d\tau\ ,\ \frac{d}{dt}z_B(t)=u_{in}(t)-u_{in}(t-\tau_B) \tag{8}$$

If we integrate the Eq.(6), the following relations are derived.

$$J=u_{in}+\Gamma_g \Delta v(z-z_B)\ ,\ \ u_l=\frac{1}{1-\alpha}\left(J-\alpha u_g\right) u_{in} \tag{9}$$

If we insert the above equations into Eq.(4) and integrate from inlet to outlet, the following equations are obtained.

$$\begin{aligned}
&\left[(L_s+L_B)\rho_l-C_o(\rho_l-\rho_g)\int_{z_B}^{L_B}\alpha\, dz\right]\frac{d}{dt}u_{in}(t)\ldots\ldots\ldots\ldots\ldots\ldots m\frac{d}{dt}u_{in}(t)\\
&-\Gamma_B\Delta v\left[(L_B-z_B)\rho_l-C_o(\rho_l-\rho_g)\int_{z_B}^{L_B}\alpha\, dz\right]\left[u_{in}(t)-u_{in}(t-\tau_B)\right]\ldots\ldots\Delta P_1\\
&-(\rho_l-\rho_g)\left[\Gamma_g v_g\int_{z_B}^{L_B}u_g\, dz-\alpha_{out}u_{gout}^2+C_o\Gamma_g\Delta v\int_{z_B}^{L_B}\alpha u_g\, dz\right]\ldots\ldots\Delta P_2\\
&+\rho_{gout}\,\alpha_{out}\,u_{gout}^2+\rho_{lout}\,(1-\alpha_{out})u_{lout}^2-\rho_{lin}u_{lin}^2\ldots\ldots\ldots\ldots\Delta P_3\\
&+\lambda_1\frac{\rho_l}{2}u_{in}^2\frac{(z_B+R_s)}{D_s}+\lambda_0\frac{\rho_l}{2}u_{inlet}^2\frac{R_{so}}{D_{so}}+\lambda_2\frac{\rho_l}{2}u_{in}^2\frac{(L_B-z_B)}{D_s}\ldots\ldots\Delta P_4\\
&+\frac{1}{2}C_R\,\rho_l\,u_{in}^2\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\Delta P_5\\
&+(L_B+L_s)\rho_l g-\left(\rho_l-\rho_g\right)g\int_{z_B}^{L_s}\alpha\, dz\ldots\ldots\ldots\ldots\ldots\ldots\Delta P_6\\
&=P_{in}-P_{out}
\end{aligned} \tag{10}$$

The void fraction is calculated by Lagrangian method.

$$\frac{D}{Dt}(\alpha)+C_o\Gamma_g\Delta v\alpha=\Gamma_g v_g \tag{11}$$

$$\frac{D}{Dt}(z)=u_g=C_o J+\overline{V_{gj}} \tag{12}$$

The variable $\frac{du_{in}(t)}{dt}$ in Eq.(10) is calculated by the following equations derived from Eq.(10) for each channel and assumption of constant total flow rate;

$$(P_{in}-P_{out})=m^{(1)}\frac{d}{dt}u_{in}^{(1)}(t)+\Delta P_T^{(1)} \tag{13}$$

....

$$(P_{in}-P_{out})=m^{(N)}\frac{d}{dt}u_{in}^{(N)}(t)+\Delta P_T^{(N)} \tag{14}$$

$$\frac{d}{dt}u_{in}^{(1)}(t)+\ldots\ldots\ldots\ldots+\frac{d}{dt}u_{in}^{(N)}(t)=0 \tag{15}$$

3. Results and Discussion

The proposed method is applied to the analysis of parallel-flow two-phase instability experiment conducted at TIT in Japan. The detailed explanation of the experimental conditions and the numerical method are given in Aritomi et al.[1] and Choi [2].

Fig.1 and Fig.2 show the time transients of the inlet velocity, when $q''=0.465MW/m^2$ and $q''=0.320MW/m^2$ and the number of channel is two, by the present method and by Aritomi et al. [1]. We can observe that the flow is unstable when $q''=0.465MW/m^2$ and is stable when $q''=0.320MW/m^2$. The results by the present method are very similar to those by the Aritomi et al. [1] although a little difference is observed in the initial time transient due to the use of different two-phase model.

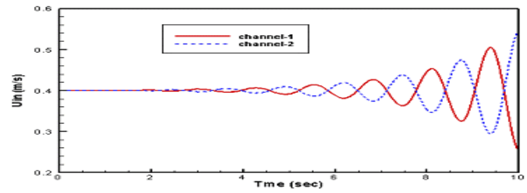
Fig.3 shows the results when the number of channel is three. Three cases are considered; (a) the case when the inlet flow rates of the first and second channel are 1:2 and the third channel is left unchanged, (b) the case when the inlet flow rate of the third channel is zero, (c) the case when the inlet flow rate of the first channel is same as that of the second channel. We can observe that the maximum amplitude of the oscillation of inlet flow rate when the number of channel is three is less than that when the number of channel is two. Although the results are not reported here (See Choi[2]), such a phenomenon is also observed when the number of channel is four. This phenomenon shows that one need to investigate the parallel-flow two-phase instability only when the number of channel is two.

4. Conclusions

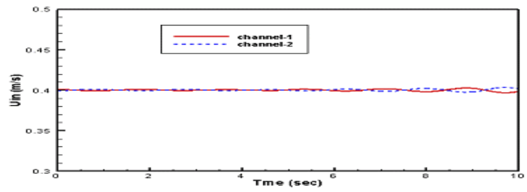
A simple method for analysis of the parallel-flow two-phase instability is proposed and the method is applied to the analysis of parallel flow instability experiment conducted at TIT. The results show that the present method predicts accurate solutions when compared with Aritomi et al. [1]. The present investigation also shows that one need to investigate the parallel flow two-phase instability only when the number of channel is two.

REFERENCES

[1] M. Aritomi, S. Aoki, and A. Inoue, "Instabilities in Parallel Channel of Forced-convection Boiling Upflow System, (I) Mathematical Model," J. Nucl. Sci. and Technol. Vol.14, pp.22-30, 1977.
[2] S. K. Choi, "Analysis of the Nonlinear Parallel Flow Two-Phase Instability in a Liquid Metal Reactor Steam Generator," KAERI Internal Report, 2006.



(a) $q''=0.465MW/m^2$



(b) $q''=0.320MW/m^2$

Fig.2 Time transients of inlet velocity by the present method when the number of channel is two

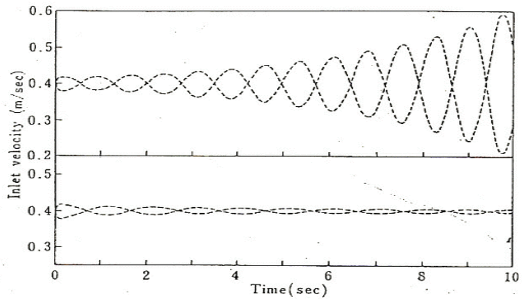
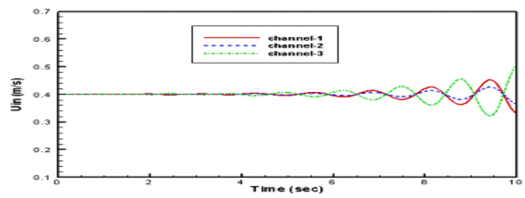
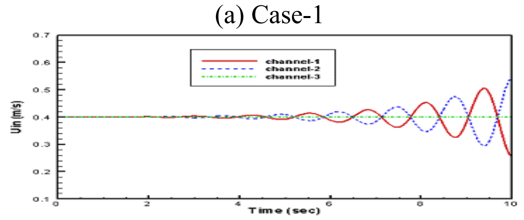


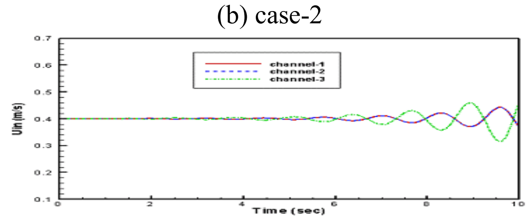
Fig.3 Time transients of inlet velocity by Aritomi et al. (upper: $q''=0.465MW/m^2$, lower: $q''=0.320MW/m^2$)



(a) Case-1



(b) case-2



(c) Case-3

Fig.4 Time transients of the inlet velocity when the number of channel is three