Flow Excursion Analysis in PAFS

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1. Introduction

Instabilities in two-phase flow system are commonplace and have been interested in by industrial concerns. It is known that the instabilities occur in the presence of both boiling and condensation processes, but in adiabatic flows[1]. In particular the possibility of two-phase flow instability in PAFS (Passive Auxiliary Feedwater System) in APR+ is now under the discussion in domestic nuclear industry.

In the classical two-phase flow instability analysis, a boiling channel in such as BWR (Boiling Water Reactor) is the major concern, and condensation process has been the outside of the interest. Recently Kolev discussed on the stability in flow condensation [2]. He mentioned the NOKO test, which simulated the emergency condensers in SWR1000, and pointed out the pressure oscillation during the test. The amplitude of the oscillation is 0.2~2.0bar and the frequency is 8~12 Hz. But he does not provide an explanation on the mechanism or the instability type.

Flow excursive instability is not only a kind of two-phase flow instability itself but also a basis of the other instabilities such as pressure drop instability. This study discusses on the flow excursion in condensation heat exchanger of PAFS, and will show the possibility of occurrence of flow excursive instability.

2. Instability and Pressure-drop Characteristics

Two-phase flow channels occasionally exhibit the particular S-shaped steady state pressure-drop-flowrate curve shown in Fig. 1.

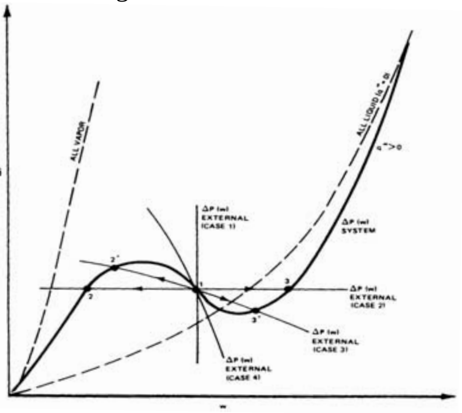

Fig. 1. Pressure drop vs. flowrate

In general the pressure drop or the pressure gradient can be calculated based on following separate flow model.

$$
\begin{aligned}
-\frac{dp}{dz} &= \frac{4\tau}{d} && (\textit{friction term}) \qquad (1)\\
&+\left\{\alpha\rho_g+(1-\alpha)\rho_l\right\} g\sin\theta && (\textit{gravitational term})\\
&+G^2\frac{d}{dz}\left\{\left(\frac{x^2}{\alpha\rho_g}+\frac{(1-x)^2}{(1-\alpha)\rho_l}\right)\right\} && (\textit{accelatation term})
\end{aligned}
$$

Considering the effect of each term in the above equation, an influence that modifies the slope of the curve can be called "destabilizing" if it makes it more negative and "stabilizing" if it tends to make it more positive.

From now on the slope of the curve will be examined

3. Examination of Pressure-drop Component

3.1 Gravitational Pressure Drop

The gravitational pressure gradient is given by

$$
\begin{aligned}
p'_{grav} &\equiv \left(\frac{dp}{dz}\right)_{grav} \qquad (2)\\
&= \left\{\alpha\rho_g+(1-\alpha)\rho_l\right\} g\sin\theta
\end{aligned}
$$

And the variation according to the flowrate is

$$
\begin{aligned}
\frac{dp'_{grav}}{d\dot{m}} &= \left(\frac{dp'_{grav}}{d\alpha}\right)\left(\frac{d\alpha}{d\dot{m}}\right) \qquad (3)\\
&= \left[\left\{\rho_g-\rho_l\right\} g\sin\theta\right]\left(\frac{d\alpha}{d\dot{m}}\right)
\end{aligned}
$$

Thus, the influence can be summarized in Table 1 according to the direction of flow and phase change direction.

Table I: Influence of gravitational pressure drop

	Upflow	Downflow
Boiling	$\left[\left\{\rho_g-\rho_l\right\} g\sin\theta\right]<0$, $and \left(\frac{d\alpha}{d\dot{m}}\right)=\left(\frac{dx}{d\dot{m}}\right)\left(\frac{d\alpha}{dx}\right)<0$ $Thus,\ \frac{dp'_{grav}}{d\dot{m}}>0$	$\left[\left\{\rho_g-\rho_l\right\} g\sin\theta\right]>0$, $and \left(\frac{d\alpha}{d\dot{m}}\right)<0$ $Thus,\ \frac{dp'_{grav}}{d\dot{m}}<0$
	Stabilizing	Destabilizing
Condensation	$\left[\left\{\rho_g-\rho_l\right\} g\sin\theta\right]<0$, $and \left(\frac{d\alpha}{d\dot{m}}\right)>0$ $Thus,\ \frac{dp'_{grav}}{d\dot{m}}<0$	$\left[\left\{\rho_g-\rho_l\right\} g\sin\theta\right]>0$, $and \left(\frac{d\alpha}{d\dot{m}}\right)>0$ $Thus,\ \frac{dp'_{grav}}{d\dot{m}}>0$
	Destabilizing	Stabilizing

Thus, as shown in Table I, a downflow condensation system has no instability mechanism in gravitational pressure drop. Of course the derivative of void fraction with respect to flowrate can be in dispute, detailed assessment is necessary.

3.2 Frictional Pressure Drop

The frictional pressure gradient is given by

$$p'_{fric} \equiv \left(-\frac{dp}{dz}\right)_F = \left(-\frac{dp}{dz}\right)_{lo} \phi_{lo}^2$$
$$p'_{lo} \equiv \left(-\frac{dp}{dz}\right)_{lo} = \frac{4}{D} f_{lo} \frac{1}{2}\frac{G^2}{\rho_l} \tag{4}$$
$$, where \ \ f_{lo} = \begin{cases} = \dfrac{16}{Re} & \text{for laminar} \\ = 0.079 Re^{-1/4} & \text{for turbulent } (\varepsilon\text{=0, } Blasius) \end{cases}$$
$$\phi_{lo}^2 = \text{Two-phase mulitplier for liquid only flow}$$

Let's examine the pressure gradient of liquid only term.

for laminar

$$\frac{dp'_{lo}}{dG} = \frac{d}{dG}\left\{\frac{4}{D}\left(\frac{16\mu}{GD}\right)\frac{1}{2}\frac{G^2}{\rho_l}\right\}$$
$$= 32\left(\frac{\mu}{\rho_l D^2}\right) > 0 \tag{5}$$

for turbulent $(\varepsilon\text{=0, } Blasius)$

$$\frac{dp'_{lo}}{dG} = \frac{d}{dG}\left[\frac{4}{D}\left\{0.079\left(\frac{GD}{\mu}\right)^{-1/4}\right\}\frac{1}{2}\frac{G^2}{\rho_l}\right]$$
$$= 0.2765 D^{-5/4}\mu^{-1/4}\rho_l^{-1}G^{3/4} > 0$$

It is evident that the pressure gradient of liquid only term is always positive regardless of the flow type.

Gradient of two-phase multiplier can be checked.

$$\frac{d\phi_{lo}^2}{dG} = \left(\frac{d\phi_{lo}^2}{dx}\right)\left(\frac{dx}{dG}\right)$$
$$= \begin{cases} < 0 & for\, boiling \\ > 0 & for\ \ condensation \end{cases} \tag{6}$$

Above result is the sign for most of the models on the two-phase multiplier except for the Martinelli-Nelson (1948) model because the two-phase multiplier increases according to the increase of quality. In Martinelli-Nelson (1948) model the slope of the two-phase multiplier changes around quality 90%. Near this quality the sign of the gradient may change, thus the flow excursion may occur.

3.3 Acceleration Pressure Drop

The frictional pressure gradient is given by

$$p'_{acc} \equiv \left(-\frac{dp}{dz}\right)_{acc}$$
$$= G^2 \frac{d}{dz}\left\{\left(\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}\right)\right\} \tag{7}$$

A derivative of the pressure gradient with respect to mass flux can be calculated as followings

$$\frac{dp'_{acc}}{dG} = 2G\frac{d}{dz}\left\{\left(\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}\right)\right\}$$
$$+ G^2\frac{d}{dz}\left\{\left(\frac{2x}{\alpha\rho_g} - \frac{2(1-x)}{(1-\alpha)\rho_l}\right)\frac{dx}{gG}\right\}$$
$$= 2\frac{d}{dz}\left\{G\left(\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}\right)\right.$$
$$\left. + G^2\left(\frac{x}{\alpha\rho_g} - \frac{(1-x)}{(1-\alpha)\rho_l}\right)\frac{dx}{gG}\right\}$$
$$= 2\frac{d}{dz}\left\{\left(\frac{Gx\left(x + G\left(dx/dG\right)\right)}{\alpha\rho_g}\right.\right.$$
$$\left.\left. + \frac{G(1-x)\left(1-x-G\left(dx/dG\right)\right)}{(1-\alpha)\rho_l}\right)\right\} \tag{7}$$

This result shows that the sign of the equation is not always positive, that is, it can be conditionally destabilizing. However, it should be emphasized that the acceleration pressure gradient is relatively smaller than the other pressure gradients. So the effect may be small.

4. Conclusions

From the examination of the pressure gradient mechanisms the influences of the each mechanism were identified. No flow excursion is expected in the downward condensation system on the whole. However further refinement of the analysis on the two-phase multiplier, the acceleration pressure gradient, and so on is necessary.

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