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Investigation on Ledinegg Instability in Condensate Tube of Passive Auxiliary Feedwater System

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1. Introduction

Passive Auxiliary Feedwater System (PAFS) is one of advanced safety features under development for Advanced Power Reactor Plus (APR+). Because the condensate flow is driven by natural circulation, it is important to ensure not to induce instabilities inside the condensate tube in PAFS for the effective cooling capability. Among the flow instabilities, the Ledinegg-type instability may cause the severe deterioration of heat removal capability of PAFS since it can reduce the condensate flow even with slight change of pressure loss. Because the Ledinegg instability occurs when the pressure drop decreases with increasing flow, to evaluate the behavior of the pressure drop according to the change of mass flow rate is essential. For this reason, one-dimensional, integrated flow model is formulated and two-phase flow characteristics in the condensate tube are mathematically solved.

2. Analysis of Ledinegg Instability

2.1. Design of Condensate Heat Exchanger

Condensation heat exchanger consists of 4 bundles and each bundle contains 60 horizontal tubes in three rows. Schematic diagram of one tube is depicted Fig. 1. The inclination of 3 degree is applied to prevent a water hammer phenomenon in the tube. Thus, flow regimes in the tube are restricted to an annular flow and horizontal stratified flow [1].

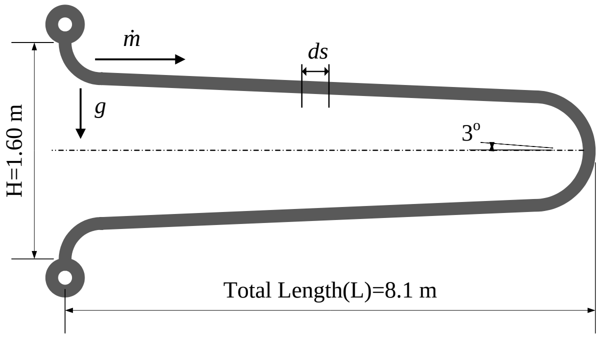

Fig. 1. Design of a heat exchanger bundle in PAFS

2.2. Analysis Condition for Ledinegg Instability

In order to analyze Ledinegg instability, one-dimensional, integrated flow model is formulated and two-phase flow characteristics in the condensate tube are mathematically solved [2]. As shown in Fig. 1, the single condensate tube is assumed for the analysis. Total length of the tube is 8.1 m and height is 1.6 m. Steam mass flow rate at the inlet of the condensate tube was determined as 0.396 kg/s [1]. Detailed data for the condensate tube is described in Table I.

TABLE I: Analysis condition of condensate tube

	Tube side	PCCT side
Pressure (bar)	78.6	2.2
Tube Diameter (m)	0.0448 (Inner)	0.0508 (Outer)
HTC Model	Jaster & Kosky	Nakajima
Quality	1.0 (Inlet)	-

2.2. Pressure Drop According to Mass Flow Rate

Because the tube lengths of single-phase and two-phase regions are changed by an inlet mass flow rate, the length of two-phase mixture region, called as the condensed length, should be calculated as follows:

$$L_{2\phi}=\frac{\dot{m}x_i h_{fg}}{\pi D_0 U_{2\phi}\Delta T_{2\phi}} \tag{1}$$

where $\Delta T_{2\phi}=T_{sat}^{tube}-T^{PCCT}$ and $x_i=\dfrac{h_{inlet}-h_f}{h_{fg}}$; T_{sat}^{tube} is the saturation temperature in the condensate tube; T^{PCCT} is the temperature of the PCCT.

According to the condensed length calculated by (1), the pressure drop terms in the momentum equation are changed and, therefore, the solution is also varied.

2.2.1. Condensed Length ≥ Tube Length

If the condensation is not fully achieved in the tube due to the high mass flow rate, there is no need to consider the single-phase region for analysis of Ledinegg instability. In this case, total pressure drop is determined by the terms related to the two-phase flow as follows:

$$\Delta P=\Delta P_{fric}^{2\phi}-\Delta P_{grav}=\frac{1}{2}\left(f\frac{L}{D_i}+K\right)\frac{\dot{m}^2}{\bar{\rho}_{2\phi}A^2}-gH\bar{\rho}_{2\phi} \tag{2}$$

where $\Delta P_{fric}^{2\phi}$ is the pressure drop due to friction in two-phase region; ΔP_{grav} is the gravitational head, respectively. $\bar{\rho}_{2\phi}$ is the averaged density defined as,

$$\bar{\rho}_{2\phi}=\frac{1}{L}\int_0^L \rho_{2\phi}(s)\,ds=\frac{1}{L}\int_0^L\frac{1}{v_f+v_{fg}\left(1-\frac{x_i-x_e}{L}s\right)}ds \tag{3}$$
$$=\frac{1}{v_{fg}(x_i-x_e)}\log\left(\frac{v_g}{v_g-v_{fg}(x_i-x_e)}\right)$$

Then, total pressure drop can be calculated from (2) and (3).

2.2.2. Condensed Length <Tube Length

In the case where the condensation is completed in the tube, the single-phase region should be considered with the two-phase region. Thus, total pressure drop is expressed with both terms of single-phase and two-phase as follows:

$$\Delta P = \Delta P_{fric}^{1\phi} + \Delta P_{form}^{1\phi} + \Delta P_{fric}^{2\phi} - \Delta P_g \qquad (4)$$

where $\Delta P_{fric}^{1\phi}$ and $\Delta P_{form}^{1\phi}$ are the pressure drop due to frictions and local form losses in single-phase region, respectively [3]. The gravitational pressure drop is given as follows:

$$\Delta P_g = g\bar{\rho}_m H = \frac{gH}{L}\left[\int_0^{L_{2\phi}} \rho_{2\phi}(s)\,ds + \int_{L_{2\phi}}^{L} \rho_{1\phi}(s)\,ds\right] \qquad (5)$$

The pressure drops by frictions and form losses are given as follows:

$$\Delta P_{irrev} = \Delta P_{fric}^{1\phi} + \Delta P_{form}^{1\phi} + \Delta P_{fric}^{2\phi} \qquad (6)$$

$$= \frac{1}{2}\left(f\frac{L}{D_i} + K\right)\frac{\dot{m}^2}{\bar{\rho}_{1\phi}A^2} + \frac{1}{2}f\frac{\dot{m}^2 L_{2\phi}}{D_i A^2}\left(\frac{1}{\bar{\rho}_{2\phi}} - \frac{1}{\bar{\rho}_{1\phi}}\right)$$

Total pressure drop can be derived from (5) and (6) as follows:

$$\Delta P = \frac{1}{2}\left(f\frac{L}{D_i} + K\right)\frac{\dot{m}^2}{\bar{\rho}_{1\phi}A^2} + \frac{1}{2}f\frac{\dot{m}^2 L_{2\phi}}{D_i A^2}\left(\frac{1}{\bar{\rho}_{2\phi}} - \frac{1}{\bar{\rho}_{1\phi}}\right) - \frac{gH}{L}\left[\frac{\dot{m}h_{fg}}{\pi D_o U_{2\phi}\Delta T_{2\phi} v_{fg}}\log\left(1 + \frac{v_{fg}}{v_f}x_i\right) + \rho_f^{PCCT}\left(L - L_{2\phi}\right)\left\{1 - \frac{\beta\Delta T_{2\phi}\dot{m}}{\left(L - L_{2\phi}\right)\xi}\left(1 - e^{-\xi\left(L - L_{2\phi}\right)/\dot{m}}\right)\right\}\right] \qquad (7)$$

2.3. Analysis Results

The calculation result for the condensed length by (1) shows that the condensed length is identical to total tube length when the mass flow rate is 0.183 kg/s. By referring this value, the pressure drop is calculated by using (7) in the low mass flow region and (2) in the high mass flow region. Figure 2 represents the frictional, gravitational, and total pressure drop with increasing mass flow rates.

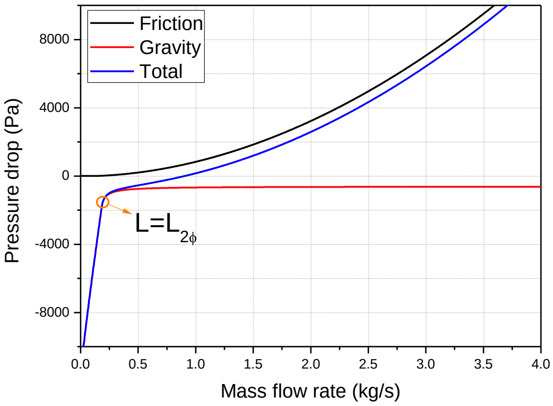

Fig. 2. Pressure drop-mass flow rate curve in the condensate tube

As shown in Fig. 2, the gravitational pressure drop shows a negative value because of downward flow. The frictional pressure drop exponentially grows with the increase of mass flow rate. Thus, total pressure drop varies from negative numbers to positive numbers but it is a monotone increasing function. This result implies that Ledinegg instability does not occur under the condition of the condensate tube in PAFS.

4. Conclusions

In this paper, the characteristics of Ledinegg instability were reviewed. Because Ledinegg instability can cause severe effects to PAFS by the sudden reduction of condensate flow, more specific attentions were given to analyze the occurrence possibility of Ledinegg instability. Analysis results showed that Ledinegg instability does not occur in the condition of downward condensation flow, which is the operating condition of PAFS.

In addition, PAFS has no occurrence possibility of the pressure wave instability since there is no occurrence possibility of Ledinegg instability. In conclusion, PAFS is stable from Ledinegg instability and other instabilities mentioned above because of its design characteristics.

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