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Dynamic Characteristics in a Reflux Condenser

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ABSTRACT

The condensate in a single vertical reflux condenser with a tube of the large L/D ratio could carried over in both ways of fill-and-dump and the annular cocurrent to steam flow. From the experimental observation made, a theoretical model based on the lumped parameter method is made to understand the dynamics of the reflux condenser. The present model predicts well the time period of fill-and-dump model and the natural vibrational frequency of the water column. This could be a first step to understand the complex phenomena in the reflux condenser such as itd improved thermal performance due to the well controlled pulsation in steam flow and the tube-to tube effect in the multi tube reflux condenser.

1. Introduction

Industrial reflux condenser has been used to condense the vapor entering into the vertical tube cooled by the shell side cooling medium. This condensate produces a film flowing downward countercurrent to vapor flow. As the vapor flow rate increases, the downward condensate flow is limited by the countercurrent flow limit(CCFL) condition in annular two-phase flow regime. The condensate accumulated in the middle of the tube is to make a water column. Oscillation and periodic dumping out of this water column could enhance or reduce the heat transfer efficiency in the reflux condenser. For the higher vapor flow rates, the direction of condensate flow changes and becomes cocurrent to vapor flow. Since only part of the vapor could be condensed in this regime, the capability of heat transfer could be limited.

During a hypothetical loss of coolant accident in the pressurized water nuclear reactor, the steam generator behaves like a reflux condenser described above to condense the steam generated in the nuclear core. According to the amount of the steam flow rate, reflux condensation and natural circulation could be observed in the steam generator tubes. The natural circulation in which the condensate may be carried along cocurrently with the steam has higher heat transfer capability than the reflux condensation. The downward condensate in the reflux condensing mode, however, could directly increase the water inventory in the nuclear reactor core. The detailed understanding of the two compete phenomena and transition between them are of importance to quantify and enhance the nuclear power

As a first step of analysis of this phenomena, the present study is performed to know the dynamics of the water column in the reflux condenser. The experimental observations were made to get the periodic pressure oscillation during the fill-and-dump period and the natural frequency of the water column oscillation in the tube by setting the pressure drop across the tube as a constant value. The analytical model proposed here is to describe these experimental data.

2. Model

In this section, a theoretical model based on the lumped parameter method is proposed from the pressure drop formulation and the mass and energy conservation equations in the reflux condenser. The present model could predicts the time period of the fill and dump mode by counting time varying from the lowest pressure drop to the highest pressure drop across the tube. Also, the perturbed equation could predicts the vibration frequency of the stable water column which could be made by keeping the pressure drop across the tube constant.

2.1 Pressure drop characteristics

As shown in Fig.4, the vapor region and liquid region are separately modelled here. To describe the oscillation, moving boundary in the two-phase region and water column is used. The vapor region includes the bottom plenum vapor region and the vapor slug in the tube. Also, the liquid region includes the water film in the two-phase region and the water column in the tube. Integrating the momentum equation along the tube gives us the following pressure drop relation:

$$
\begin{aligned}
P_0 - P_e = {} & \left(\frac{l_{1p} + 2\, l_{2p}}{2 A_{tb}}\right)\frac{dW^*}{dt} + \frac{1}{2}\left((\rho_f + \rho_{2p})\, l_{2p} + \rho_{2p}\, l_{2p}\right)\frac{d^2 l_{2p}}{dt^2} \\
& + \frac{\rho_f}{2}\left(\frac{dl_{2p}}{dt}\right)^2 + \left(K - \frac{1}{2}\right)\left(\frac{W_{st}^2}{2\rho_g A_{tb}^2} + \frac{W_{fl}^2}{2\rho_f A_{tb}^2}\right) \\
& + \frac{f_2\, l_{2p}}{4D}\left(\frac{W_{st}^2}{\rho_g A_{tb}^2} - \frac{W_{fl}^2}{\rho_f A_{tb}^2} + \rho_{2p}\left(\frac{dl_{2p}}{dt}\right)^2 + 2\left(\frac{d\, l_{2p}}{dt}\right)\left(\frac{W^*}{A_{tb}}\right) + \frac{1}{\rho_{2p}}\left(\frac{W^*}{A_{tb}}\right)^2\right) \\
& + \frac{8\pi\mu\, l_{1p}}{A_{tb}}\left(\frac{1}{2}(\rho_f + \rho_{2p})\frac{dl_{2p}}{dt} + \frac{W^*}{2 A_{tb}}\right) + (\rho_f\, l_{1p} + \rho_{2p}\, l_{2p})g
\end{aligned}
\qquad (1)
$$

2.2 The fill and dump mode

(a) The maximum pressure drop

Applying the maximu, pressure drop boundary conditions to Eq. (1), the pressure drop relation becomes :

$$
\Delta P = \frac{f_{2p} h_{fg}}{16\rho_g A_{tb}^3 U\sqrt{\alpha}\Delta T} W_{st}^3 + \frac{(K - 1)}{2\rho_g A_{tb}^2} W_{st}^2 - \frac{(\rho_f - \rho_{2p}) g\, h_{fg}}{\pi D U \sqrt{\alpha}\Delta T} W_{st} + \rho_f g H \qquad (2)
$$

(b) The minimum pressure drop

The pressure drop locus then becomes

$$
\Delta P = \frac{\left(K + \frac{f_{2p} H}{2D}\right)}{\rho_g A_{tb}^2} W_{st}^2 + \rho_{2p} g H \qquad (3)
$$

(c) The period of the fill and dump mode

To determine the one complete period of the fill-and-dump cycle, the total mass conservation equation of the reflux condenser system is integrated through one cycle period :

$$\tau = \frac{M(\tau) - M(0)}{W_{st} - \frac{1}{\tau}\int_0^{\tau} W_{fl}(t)dt} \tag{4}$$

$$\tau = \frac{A_{tb}}{g\left(W_{st} - W_{fl}\right)}\left(\Delta P - \frac{f_{2p}\,h_{fg}\,W_{st}^{3}}{16\,\rho_g\,A_{tb}^{3}\,U\sqrt{\alpha}\Delta T} + \frac{\left(1 + \frac{f_{2p}H}{D}\right)W_{st}^{2}}{2\,\rho_g\,A_{tb}^{2}}\right) \tag{5}$$

2.3 The natural frequency of the water column oscillation

To obtain the natural frequency of the quasi-steady water column oscillation, the following small perturbation is introduced to Eq. (1) :

$$\begin{aligned} P &= P_o + dP \\ l_{2p} &= l_{2p}^{0} + dl_{2p} \\ X &= dl_{2p} \end{aligned}$$

the following linear ordinary equation is obtained :

$$\left(\frac{\rho_{2p}\left(l_{1p} + l_{2p}\right)}{2} + \rho_f\,l_{1p}\right)X_{tt} + \frac{8\pi\mu\,l_{1p}}{A_{tb}}\left(\frac{\rho_f + \rho_{2p}}{2}\right)X_t + \frac{\alpha\,A_{tb}\,\rho_g}{V_g^{0}\left(\frac{\partial\rho_g}{\partial p} + \frac{\rho_g}{h_{fg}}\frac{\partial h_g}{\partial p}\right)}X = 0 \tag{6}$$

From the above equation, the frequency of the water column oscillation is obtained as

$$\omega = \frac{1}{2\pi}\sqrt{\frac{\alpha\,A_{tb}\,\rho_g}{\left(\frac{\rho_{2p}}{2}(l_{2p} + l_{1p}) + \rho_f\,l_{1p}\right)V_g^{0}\left(\frac{\partial\rho_g}{\partial p} + \frac{\rho_g}{h_{fg}}\frac{\partial h_g}{\partial p}\right)} - \frac{\left(\frac{8\pi\mu\,l_{1p}}{A_{tb}}\right)^{2}\left(\frac{\rho_f + \rho_{2p}}{2}\right)^{2}}{4\left(\frac{\rho_{2p}}{2}\left(l_{2p} + l_{1p}\right) + \rho_f\,l_{1p}\right)^{2}}} \tag{7}$$

The above relationship could be simplified by removing the small terms as follows:

$$\omega = \frac{1}{2\pi}\sqrt{\frac{\alpha A_{tb}\rho_g}{\left(\frac{\rho_{2p}}{2}(l_{2p} + l_{1p}) + \rho_f l_{1p}\right)V_g^0\left(\frac{\partial\rho_g}{\partial p}\right)}} \qquad (8)$$

3. Conclusions

A general understanding on the dynamics of the reflux condenser is obtained through the lumped parameter model. Fill-and-dump mode is explained with the pressure build up due to water column make-up process. Also, the vibration of the free standing water column is modelled and its frequency has the similarity to the spring with damper. From the whole mathematical derivation it could be possible to apply to the dynamic analysis of reflux condenser dynamics.

4.Acknowledgement

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5. References

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