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Analysis of single phase flow instability in U-tubes of steam generator

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ABSTRACT

Based on the one-dimensional thermal hydraulic model for U-tubes under natural circulation, the flow characteristic of the single phase fluid in the parallel U-tubes is studied. The critical pressure drop (CPD) and critical mass flow rate (CMFR) are also given and analyzed, which relate to the occurrence of reverse flow in U-tubes and are influenced by the inlet temperature. The U-tubes in marine and commercial steam generators are chosen to investigate the effect of inlet temperature on the flow instability. It is found that (1), the CMFR increases and the CPD decreases with the increase of the inlet temperature, (2) the inlet temperature has great influence on the space distribution of reverse flow in the marine steam generator with the small size, but it has little influence on that in the commercial steam generator with the large size.

1. Introduction

Under the normal operation or accident conditions, natural circulation usually can be used as a significant way to cool the reactor core (Hao et al., 2012). Existing literatures show that the single phase flow in some parallel U-tubes of steam generator (SG) may be instable under the natural circulation conditions, and the reverse flow will occur, which will bring negative influence on the reactor safety (Chen et al., 2013). The reverse flow in U-tubes belongs in the category of Ledinegg-type flow instability, which can be studied by deriving the hydrodynamic curve of pressure drop with velocity (or mass flow rate) in the parallel U-tubes (Jeong et al., 2004). Wang and Yu (2010) analyzed the space distribution of the reverse flow U-tubes and the sensibility of the U-tube length by the code RELAP/MOD3.3. Zhang et al. (2011) and Hao et al. (2013a) found that the relationship between critical pressure drop and U-tube length is nonlinear and the effects of U-tube length on the reverse flow in the marine and commercial SGs are different. Hao et al. (2014b) also investigated the flow instability in U-tubes of SG based on CFD method, the results showed that the reverse flow in U-tubes was closely related to the inlet subcooling and U-tube length. Hao et al. (2013b, 2014a) and Chu et al. (2014a, 2016) found that the movement of ships also affected the reverse flow for marine steam generator, which was markedly different from nuclear power plant on shore. Using the hydrodynamics characteristics curve of parallel U-tubes, Yang et al. (2010) successfully developed a lumped-distributed model to calculate the reverse flow for real steam generator with a large number of U-tubes. The reverse flow in some U-tubes means the cooled fluid in the outlet plenum of SG may flow back to the inlet plenum, which changes the inlet temperature (the fluid temperature at U-tube inlet in this paper) of the parallel U-tubes, so it is important to analyze the effect of inlet temperature on the flow instability in U-tubes of SG.

In this paper, the one-dimensional thermal hydraulic model in U-tubes is established, the flow characteristic in parallel U-tubes is studied and the relationships between the flow instability criterion and inlet temperature are analyzed. For single phase flow instabilities, the coupled effects of inlet temperature and U-tube length on the reverse flow in SGs are investigated. And the space distributions of reverse flow U-tubes in the marine and commercial SGs are given, respectively.

2. Flow characteristic in parallel U-tubes

Fig. 1 shows the diagram of parallel U-tubes. While the fluid mass flow rate is given, the pressure drop between the exit and entrance of U-tubes can be expressed as follows (Jeong et al., 2004):

$$\Delta p = \left(\frac{fl}{d_0} + \xi\right)\frac{\dot{m}^2}{2A^2\bar{\rho}} - \Delta\rho g H \quad (1)$$

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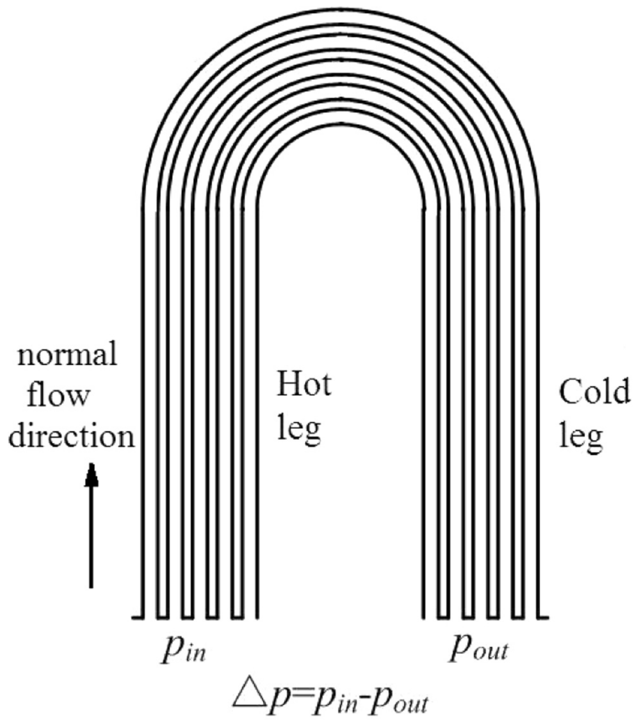

Fig. 1. Diagram of parallel U-tubes.

where $\dot{m}$ is the mass flow rate, f is the frictional resistance coefficient of the U-tube wall, $f = 0.3164\mathrm{Re}^{-0.25}$, Re is the Reynolds number, l is the U-tube length, d_0 is the U-tube inside diameter, ζ is the local resistance coefficient, $\zeta = 0.262 + 0.326(d/r_u)^{3.5}$ (Chen et al., 2013), r_u is the radius of U-tube bending part, A is the U-tube flow area, $\bar{\rho}$ is the average density, $\Delta\rho$ is the density difference between the cold and hot legs of the U-tube, g is the gravitational acceleration, H is the U-tube height. The first term in the right-hand side of Eq. (1) is the flow resistance, and the last term represents the gravitational pressure drop. Because the acceleration pressure drop is negligible in comparison with other terms (Jeong et al., 2004), its contribution to the total pressure drop is not considered in this analysis.

Based on Boussinesq approximation, the density of fluid in the U-tube can be written as follows (Sanders, 1988):

$$\rho = \rho_0(1 - \beta(T - T_w)) \tag{2}$$

where ρ_0 and T_w are the reference density and temperature, respectively, β is the thermal expansion coefficient.

While the inlet temperature and mass flow rate are given, the fluid density can be written as follows (Chu et al., 2014b):

$$\rho = \rho_0 - (\rho_0 - \rho_{in})e^{-\frac{h_{sp}Ps}{\dot{m}c_p}} \tag{3}$$

where ρ_{in} is the fluid inlet density, c_p is the specific heat capacity, s is the coordinate in the normal flow direction along the U-tube, P is the wetted perimeter of the U-tube, h_{sp} is the overall heat transfer coefficient between the inner and external fluid of the U-tube, $h_{sp} = \frac{1}{\frac{1}{h_0} + \frac{d_0}{2\lambda_{wall}}\ln(\frac{d_1}{d_0}) + \frac{d_0}{h_1 d_1}}$, h_0 is the surface heat transfer coefficient on the U-tube inside, λ_{wqll} is the U-tube heat conductivity coefficient, d_1 is the U-tube outside diameter, h_1 is the surface heat transfer coefficient on the U-tube outside.

From Eq. (3), we have

$$\bar{\rho} = \int_0^l \rho \cdot ds \Big/ l = \rho_0 - (\rho_0 - \rho_{in})\frac{\dot{m}c_p}{h_{sp}Pl}\left(1 - e^{-\frac{h_{sp}Pl}{\dot{m}c_p}}\right) \tag{4}$$

$$\begin{aligned}\Delta\rho &= \left(\int_{l/2}^{l} \rho \cdot ds - \int_0^{l/2} \rho \cdot ds\right)\Big/ l/2 \\ &= \rho_0 - (\rho_0 - \rho_{in})\frac{2\dot{m}c_p}{h_{sp}Pl}\left(1 - e^{-\frac{h_{sp}Pl}{2\dot{m}c_p}}\right)^2\end{aligned} \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (1), the expression of the pressure drop can be derived as follows:

$$\begin{aligned}\Delta p = &\frac{\dot{m}^2(fl/d_0 + \zeta)/(2A^2)}{\rho_0 - \frac{(\rho_0 - \rho_{in})c_p\dot{m}}{h_{sp}Pl}\left(1 - e^{-\frac{h_{sp}Pl}{\dot{m}c_p}}\right)} \\ &- \frac{(\rho_0 - \rho_{in})c_p\dot{m}}{h_{sp}Pl/2}\left(1 - e^{-\frac{h_{sp}Pl}{2\dot{m}c_p}}\right)^2 gH\end{aligned} \tag{6}$$

According to Eq. (6), the relation curve of the Δp with mass flow rate in the U-tube is shown in Fig. 2.

It can be seen form Fig. 2 that the curve of the pressure drop with mass flow rate has a negative slope region and a minimum at the point C. The flow direction is positive when the U-tube operates at the right side region of the point C (Hao et al., 2013a). On the contrary, when the U-tubes operate at the left side region of the point C (the negative slope region), the flow will be unstable and the reverse flow may occur. The pressure drop and mass flow rate corresponding to the point C are called as the critical pressure drop (CPD) and critical mass flow rate (CMFR), respectively.

In order to obtain the CPD (Δp_c) and CMFR ($\dot{m}_c$), $\frac{\partial \Delta p}{\partial \dot{m}} = 0$ should be solved, then the following equations can be obtained:

$$\begin{aligned}0 = &\frac{\dot{m}_c\left(\frac{fl}{d_0} + \zeta\right)\left[\rho_0 - (\rho_0 - \rho_{in})\left(\frac{1 - A_1^2}{2\ln A_1} + A_1\right)\right]}{A^2\left[\rho_0 + \frac{(\rho_0 - \rho_{in})}{2\ln A_1}(1 - A_1^2)\right]^2} \\ &+ \frac{(\rho_0 - \rho_{in})gH(1 - A_1)}{\dot{m}_c}\left(\frac{1 - A_1}{\ln A_1} - 2A_1\right) = 0\end{aligned} \tag{7}$$

$$\Delta p_c = \frac{\dot{m}_c^2(fl/d_0 + \zeta)/(2A^2)}{\rho_0 + \frac{(\rho_0 - \rho_{in})}{2A_1}(1 - A_1^2)} + \frac{(\rho_0 - \rho_{in})}{A_1}(1 - A_1)^2 gH \tag{8}$$

where $A_1 = e^{-\frac{h_{sp}Pl}{2\dot{m}_c c_p}}$.

While the mass flow rate or the pressure drop in U-tube is lower than $\dot{m}_c$ or ΔP_c, the flow is unstable, and the reverse flow will occur in the U-tube. It can be seen from Eqs. (7) and (8) that ρ_{in} has large influence on the CMFR and CPD. Because the water density in the

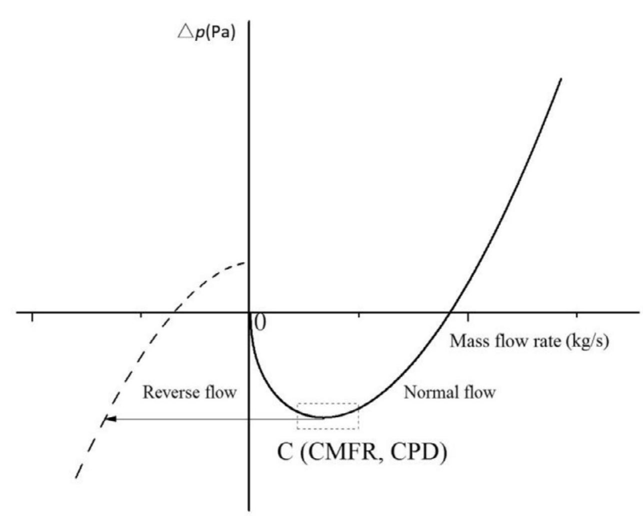

Fig. 2. Relation curve of pressure drop with mass flow rate in a U-tube.