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Effect of U-tube length on reverse flow in UTSG primary side under natural circulation

Jianli Hao, Wenzhen Chen *, De Zhang

Department of Nuclear Energy Science and Engineering, Naval University of Engineering, Wuhan 430033, PR China

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ABSTRACT

For natural circulation, it is shown that parallel flow in the tubes of inverted U-tube steam generators may be non-uniform, and reverse flow occurs within some U-tubes. However the current researches on the mechanism and space distribution of reverse flow in the U-tubes gave different results. In present work, a model of one-dimension and steady state flow is proposed, which can be used to analyze the effect of U-tube length on reverse flow in UTSG primary side under natural circulation. According to the linear micro-disturbance theory, the mechanism of reverse flow is studied. The relationships between U-tube length and critical pressure drop and critical velocity are nonlinear, at which the flow instability happens. There exists a critical U-tube length which has the maximal absolute value of critical pressure drop. The results are validated by the best estimate code RELAP5/MOD3.3.

1. Introduction

The complex set of physical phenomena that occur in a gravity environment when a geometrically distinct heat sink and heat source are connected by a fluid flow path can be identified as natural circulation (IAEA, 2005). Natural circulation can be used as a means of cooling the reactor core under the normal operation or accident conditions. Also, several advanced water cooled reactors incorporate passive safety systems based on natural circulation. As an essential component of natural circulation system (NCS), the natural circulation vertical U-tube steam generator (UTSG) is widely used in PWRs and PHWRs. For the certain classes of accidents/transients that involve an early trip of reactor coolant pumps, the core heat is transported by natural circulation into the steam generators, which act as the major heat sink. The flow rate in a steam generator (SG) under the natural circulation is always much smaller than that under the normal operation condition. Two-phase natural circulation or reflux condensation may occur if the accidents involve a loss of the reactor coolant. These conditions can make the flow and heat transfer in the steam generator much more complicated.

Non-uniform flow distribution within tubes of UTSG was found on several large scale test facilities (LSTFs) or integral system test facilities (ISTFs) under the natural circulation experiments. Kukita et al. (1988) performed two experiments in the LSTF to investigate the natural circulation behavior of a PWR with inverted U-tubes. In the experiments, the three major natural circulation modes were observed during the decrease of mass flow rate in the primary side: single-phase liquid natural circulation, two-phase natural circulation, and reflux condensation. For all those circulation modes and the transitions among the modes, the mass flow distribution in the steam generator U-tubes was significantly non-uniform. Reverse or stagnant flow in the steam generator U-tubes was observed in the natural circulation experiment, Test A2-77A, and in the LOBI-MOD2 integral system test facility of PWR (De Santi and Leva, 1985). In addition to these experiments, non-uniform flows in U-tubes were found in the BETHSY and PKL III test facilities (Jeong et al., 2004). The different experiments were also made on the natural circulation test facility in Nuclear Power Institute of China (NPIC). The results indicated that the resistance characteristics under the single-phase natural circulation are more complicated than that under the single-phase forced circulation (Wang et al., 2007; Chen et al., 2012).

Sanders (1988) developed a mathematical model to analyze the non-uniform flow behavior during single-phase natural circulation. Jeong et al. (2004) developed a flow model to analyze the single- and two-phase flow characteristics in the primary side of UTSG. By using the flow model, the relationship between pressure drop and mass flow rate is derived. The studies show that the relationship has a negative slope and flow excursion instability will occur under certain low-flow conditions.

But up to the present, the researches on the space distribution of reverse flow in U-tubes have not given the consistent conclusion. Jeong et al. (2004) considered the flow excursion or reverse flow will occur in the longer tube earlier. Yang et al. (2010)

* Corresponding author. Present address: Faculty 301, Department of Nuclear Energy Science and Engineering, Naval University of Engineering, Wuhan 430033, PR China. Tel.: +86 027 13871167436.

E-mail address: Cwz2@21cn.com (W. Chen).

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analyzed the mechanism of reverse flow by using the full range characteristic curve of parallel U-tubes. They considered that the flow in UTSG could not keep on if the reverse flow occurred in shorter tubes. However by using CFD method, Zhang et al. (2009) investigated the flow characteristics and found the reverse flow occurs in the shorter tubes. Based on the best estimate code RELAP5/MOD3.3, Wang and Yu (2010) and Zhang et al. (2010) concluded the reverse flow occurs in the shorter tubes too, so it is necessary to study the effect of U-tube length on the UTSG primary side reverse flow.

Generally, there are several thousands of vertical inverted U-tubes in UTSG, and the tube lengths are significantly different. In present work, a flow model of one-dimension, single phase, steady state is proposed to study the effect of U-tube length. Further analysis shows that tube length can significantly influence the relationship between the critical pressure and velocity for the different tubes during the flow excursion. Finally, the results are validated by the best estimate code RELAP5/MOD3.3.

2. Mathematical model

Fig. 1 shows the schematic of inverted U-tube steam generators under the natural circulation. Because the relationship between the tube length L and inner diameter d_i satisfies $L \gg d_i$, it is acceptable to establish one-dimension thermal–hydraulic model of fluid within tubes, which is shown as Fig. 2. The coordinate S is along the forward flow direction, the fluid parameter $X(s)$ is the surface average value. It is assumed that (1) the fluid is Newtonian and incompressible, (2) the density difference is considered only in the gravity body force term, (3) the density change is induced by the changes of temperature and not by pressure, (4) the heat conduction in the liquid is neglected, (5) the heat storage in tube walls is neglected, and (6) the heat generation caused by friction is neglected.

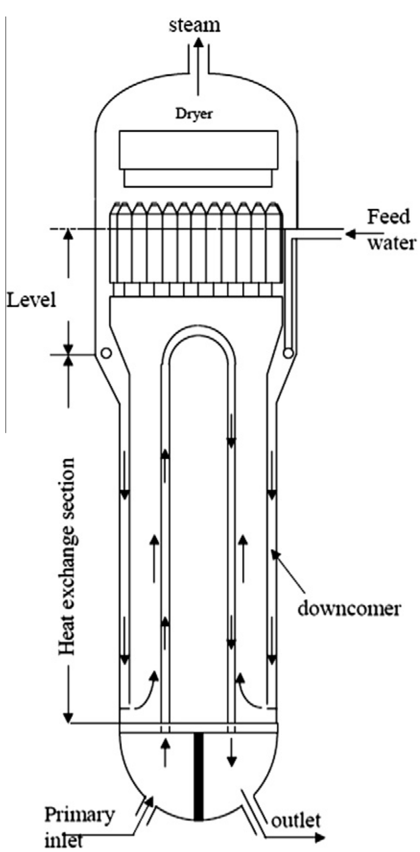

Fig. 1. Inverted U-tube steam generators (taken from IAEA-TECDOC-1474).

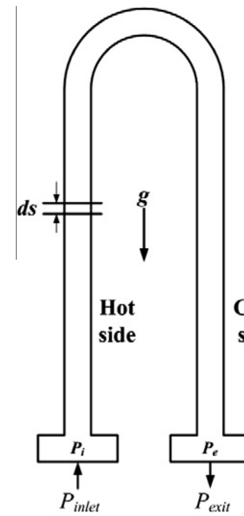

Fig. 2. Primary side modeling of tube.

Based on Boussinesq approximation, the density $\rho = \rho(T)$ can be written as follows:

$$\rho(T) = \rho_0(1 - \beta(T - T_0)) \tag{1}$$

where T_0 is the reference temperature, K; ρ_0 is the density at the operation pressure and reference temperature, kg/m^3; β is the thermal expansion coefficient, 1/K.

The conservation equations are given as follows:

Mass conservation equation:

$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0 \tag{2}$$

Momentum conservation equation:

$$\rho\frac{Dv}{Dt} = -\frac{\partial p}{\partial s} - F_f \mp \rho g \tag{3}$$

Energy conservation equation:

$$\rho c_p\frac{DT}{Dt} = \frac{\partial}{\partial s}\left(\lambda\frac{\partial T}{\partial s}\right) \tag{4}$$

where ρ is the density, kg/m^3; t is the time, s; v is the velocity, m/s; s is the coordinate location, m; p is the pressure, Pa; g is the gravity, m/s^2; F_f is the resistance in unit volume, including friction and local resistance, N/m^3; c_p is the specific heat, J/(kg K). $\frac{D}{Dt}$ is the material derivative, in one-dimension model, the form of material derivative is $\frac{D}{Dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial s}$.

Because the fluid is incompressible, the mass conservation equation is given by $\nabla \cdot v = 0$, and the one-dimension mass conservation equation can be written as follows:

$$\frac{\partial v}{\partial s} = 0 \tag{5}$$

Which means the velocity v is constant over the length of tube. The heat transfer coefficient is:

$$K = \frac{1}{\frac{1}{\alpha_i}\frac{d_o}{d_i} + \frac{d_o}{2\lambda_{wall}}\ln\frac{d_o}{d_i} + \frac{1}{\alpha_o}} \tag{6}$$

Based on Newton's law of cooling, the heat flux is:

$$q'' = -K(T - T_s) \tag{7}$$

The energy conservation equation can be written as follows: