Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Analysis of a Potential Two-Phase Flow Instability in a PWR Passive Auxiliary Feedwater System

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1. Introduction

The APR+ incorporates a passive auxiliary feedwater system (PAFS) [1]. The PAFS is comprised of two separate mechanical divisions. Each division is a closed loop which is aligned to feed condensed water to its corresponding steam generator (SG), and is equipped with one passive condensation heat exchanger (PCHX), some associated isolation/drain/vent valves, check valves, instrumentation and control, and pipes.

The PAFS is designed to start its operation after reactor trip and maintain its function of residual heat removal for 8 hours or longer without AC power or operator action, and to ensure a subsequent cooldown of RCS to the shutdown cooling entry conditions. During the PAFS operation mode, steam in the SG secondary side moves up due to buoyancy force and passes through the main steam line, and then flows into the PCHX where steam is condensed inside the tubes of which the outer wall surfaces are cooled by the water stored in a condensation cooling tank. The condensate is passively fed into the SG economizer by gravity.

Because a natural circulation loop is susceptible to two-phase flow instability, it is requisite to confirm the PAFS is designed adequately to avoid the potential challenges to its operational safety due to the instability. This paper addresses an analytical model for assessing if the loop has possible thermal and fluid mechanical characteristics which could lead to an undesirable unstable or oscillating water level in the APR+ PAFS.

2. Methods and Results

For simplicity, the analysis model of the natural circulation loop representing the PAFS is designed as shown in Fig. 1.

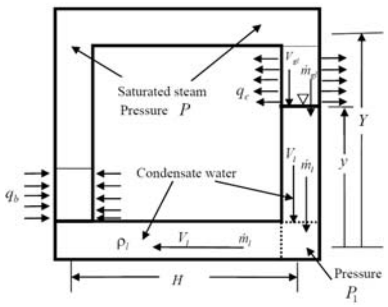


Fig. 1 Simplified analysis model of the PAFS

The water is boiled to steam in the lower left corner modeled for the SG. It flows upward in the left vertical pipe, and horizontally across to the right vertical pipe section between elevation Y and the liquid level y. In this upper part of the vertical section corresponding to the PCHX, heat transfer occurs outward to the atmosphere from the loop, condensing all the steam. The condensate water maintains its level at y in the right vertical pipe.

2.1 Governing Equations

Figure 2 shows the simplified control volumes of the part of PAFS containing condensate water. All of the flow resistance is lumped together in the horizontal section, and is designated as a total pressure loss ΔP_l.

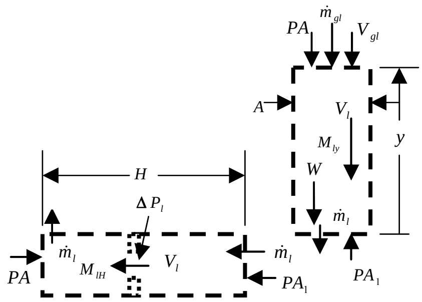


Fig. 2 Control volumes around the condensate water

For considering the boiling in the SG, the condensate water flowing out of the left outlet of the horizontal control volume is assumed to be heated immediately and boiled to saturated steam at pressure P in the lower part of the vertical column on the left side. The pressure P is assumed to act throughout the entire steam flow path to the top surface of the water in the vertical column on the right side.

From the mass and momentum conservations for the vertical and horizontal water sections [2] and the condensation heat transfer rate q_c, the following governing equations can be derived.

$$V_l - \beta(Y-y) + \frac{dy}{dt} = 0 \quad (1)$$

$$\frac{(K_L+2)}{2}V_l^2 + (y+H)\frac{dV_l}{dt} - \beta^2(Y-y)^2 - gy + V_l\frac{dy}{dt} = 0 \quad (2)$$

where, the liquid velocity V_l, condenser performance parameter β, and loss coefficient K_L are given by

$$V_l = \dot{m}_l/\rho_l A, \quad \beta = hp_w\Delta T/(h_{gl}A\rho_l), \quad K_L = 2g_0\Delta P_l/(\rho_l V_l^2) \quad (3)$$

2.2 Steady State Solution

Solving the steady flow equations for y_0 and V_{l0},

$$y_0 = Y - g(\sqrt{1+2YK_L\beta^2/g}-1)/K_L\beta^2 \quad (4)$$

$$V_{l0} = \beta(Y - y_0) \quad (5)$$

2.3 Unsteady State Solution

Unsteady solutions of the problem can be written as perturbations about the steady state in the forms,

$$y(t) = y_0 + \varepsilon y_1(t) + \cdots \ , \ V_l(t) = V_{l0} + \varepsilon V_{l1}(t) + \cdots \quad (6)$$

Substituting Eqs. (6) into Eqs. (1) and (2), the first order perturbation forms can be obtained as,

$$V_{l1} + \beta y_1 + \frac{dy_1}{dt} = 0 \quad (7)$$

$$(2+K_L)V_{l0}V_{l1} + (y_0+H)\frac{dV_{l1}}{dt} + \left[2\beta^2(Y-y_0)-g\right]y_1 + V_{l0}\frac{dy_1}{dt} = 0 \quad (8)$$

From Eqs. (7) and (8), the following second order governing differential equation for the water level y_1 as,

$$\frac{d^2y_1}{dt^2} + C_D\frac{dy_1}{dt} + \omega^2 y_1 = 0 \quad (9)$$

$$C_D = \beta + (K_L+1)V_{l0}/(y_{l0}+H) \quad (10)$$

$$\omega = \sqrt{[(K_L+2)V_{L0}\beta - 2\beta^2(Y-y_0)+g]/(y_0+H)} \quad (11)$$

A general solution to Eq. (9) can be given as

$$y_1(t) = (a_0\cos\Omega t + b_0\sin\Omega t)e^{-\frac{C_D}{2}t} \quad (12)$$

where

$$\Omega = \sqrt{\omega^2 - (C_D/2)^2} = \omega\sqrt{1-(C_D/2\omega)^2} \quad (13)$$

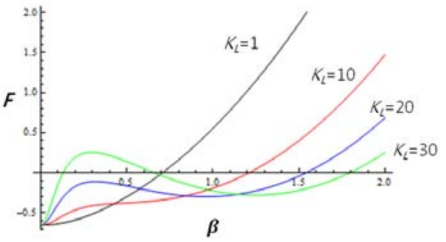
2.4 Criteria for Determining the System Instability

The critical damping occurs at the value of $C_{D,crit} = 2\omega$ for which the square root of Eq. (13) becomes zero. When the value of C_D is larger than 2ω (i.e. $C_{D,over} \geq 2\omega$), critical or over-damping occurs while lower values refer to under-damping. Thus, to avoid the possible two-phase instability in the PAFS design, the present critical or over-damping criteria should be met.

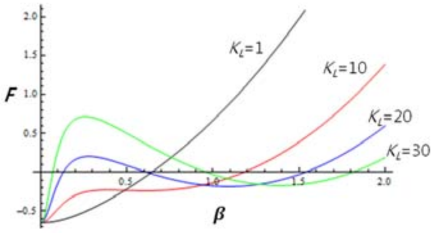
A function $F(\beta, Y, H) = C_D^2 - (2\omega)^2$ was used to determine the system instability in this study. Based on the present damping criteria for the PAFS, the potential instability was assessed for a limited range of the geometrical and operational parameters as an illustration. Fig.3 shows the acceptable ranges of β ($F \geq 0$) that the system instability does not occur for the specified values of Y and K_L. As the value of Y or K_L increases, the acceptable range of β for stable operation expands in the practical range of β (<1.0).

3. Conclusions

Both steady-state and unsteady analytical solutions for a simplified natural circulation loop model of the PAFS were derived in terms of the condensate water level and velocity in the vertical pipe section. From the solutions, the criteria for determining a potential for two-phase instability in the PAFS were obtained.



(a) Y = 20 m



(b) Y = 30m

Fig.3 Effects of β and K_L on the PAFS instability

The unsteady water level solution implies that there may be some ranges of geometrical or operational parameters which could lead to oscillatory water level and velocity in the condensate water section. Thus, further detailed investigation either by analysis or experiment is needed to confirm if the PAFS will not be threatened by the unacceptable two-phase instability during its demanded operation mode.

REFERENCES

[1] KHNP, APR+ Standard safety Analysis Report, KHNP, Seoul, pp. 10.4-28-2011.
[2] F. Moody, Introduction to Unsteady Thermofluid Mechanics, John Wiley & Sons, New York, 1990.

<u>*Nomenclature*</u>

A : cross-sectional area of the pipe
C_D : damping coefficient
g : gravity
h_c : condensation heat transfer coefficient
h_{gl} : latent heat
q_c : condensation heat transfer rate $(= h_c p_w (Y-y)\Delta T)$
T_{sat} : saturation temperature in the PAFS
T_∞ : condenser tube ambient temperature
t : time
V_{l0} : steady-state liquid velocity
$V_{l1}(t)$: unsteady term of liquid velocity
y_0 : steady-state water level
$y_1(t)$: unsteady term of water level
ρ_l : liquid density
ω : circular frequency (radians/sec)
ΔT : temperature difference $(= T_{sat} - T_\infty)$