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Assessment of a Potential Rapid Condensation-induced Waterhammer in a Passive Auxiliary Feedwater System

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1. Introduction

A passive auxiliary feedwater system (PAFS) which is incorporated in the APR+ system is a kind of closed natural circulation loop [1]. The PAFS has no operating functions during normal plant operation, but it has a dedicated safety function of the residual heat removal following initiating events, including the unlikely event of the most limiting single failure occurring coincident with a loss of offsite power, when the feedwater system becomes inoperable or unavailable. Even in the unlikely event of a station blackout, the isolation valves can be opened either by DC power or manual operation and then the PAFS can also provide adequate condensate to the steam generator (SG).

The PAFS piping in the vicinity of each of the two SGs is designed to minimize the potential for destructive water hammer during start-up operation by setting the stroke time for full close or full open of the condensate isolation valves upon receipt of a passive auxiliary feedwater actuation signal. The temperature of the stagnant condensate water and its surrounding tubes and piping during the reactor normal operation modes may fall to the ambient temperature.

A possible concern is the introduction of saturated steam into the PAFS recirculation pipe downstream of the PCHX in the beginning of the PAFS operation. Although the steam introduction rate is expected to be slow, a rapid condensation rate is expected due to the initial cold surrounding temperature in the pipe, which could result in a localized pressure reduction and the propagation of decompression and velocity disturbances into the condensate water leg, which might cause the sudden closure of check valves and associated waterhammer. Thus, it is requisite for the licensing review of the PAFS design to confirm if destructive waterhammers will not be produced due to such rapid condensation-induced decompressions in the system.

This paper addresses an assessment of the potential local decompressions which could result from the steam condensation and the associated velocity disturbances in the water column.

2. Methods and Results

2.1 A Simple Analysis Model

When the PAFS performs its function, the primary coolant flowing through the SG tube side transfers the residual heat to the SG shell-side coolant.

The SG shell-side water is heated up to its saturation temperature and begins to boil producing the mixture (saturated steam) flowing upwards due to buoyancy force. The saturated water separated by the moisture separator(s) which is installed at the top location inside the SG is returned into the SG downcomer, while the high quality steam exiting the SG outlet goes to the PCHX and flows inside the PCHX tubes through which the vapor condenses by losing its latent heat. The latent heat transferred to the tank-side water in the PCCT of which the top is open to atmosphere is dissipated as sensible heat to heat up the water and then as latent heat to evaporate the saturated tank-side water into the atmosphere. The condensed PAFS coolant flows down through the vertical piping connecting the PCHX and the SG economizer feedwater line due to gravity.

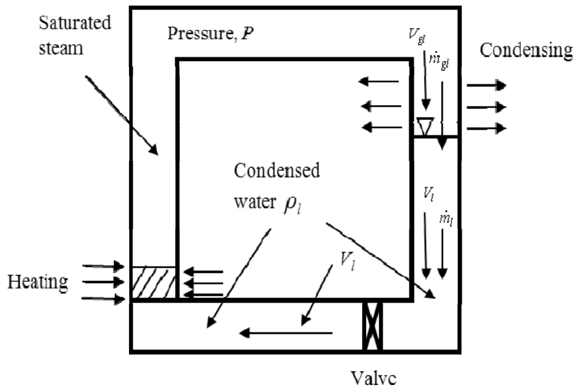

Fig. 1 Simplified analysis model of the PAFS

For simplicity, the analysis model of the natural circulation loop representing the PAFS is designed as shown in Fig. 1, where water is boiled to steam in the lower left corner functioning as the SG. It fills the piping up the condenser. When the valve in the lower horizontal leg opens to activate the PAFS, the saturated steam moves into the PCHX and is condensed water. In this process, some steam can be entrained in the flow into the vertical leg downstream of the PCHX, heat transfer occurs to the cool pipe, and condensation occurs.

2.2 Waterhammer Analysis Model

The rapid condensation of steam results in removal of the steam in the flow field, which acts like a steam leakage causing a local pressure reduction. The resulting decompression disturbance propagates in both the steam and water. Thus, it is necessary to calculate the magnitudes of the decompression and velocity disturbances for assessing the potential for water-hammer damage which may be caused by the rapid condensation of steam in the downstream of the PAFS.

The velocity disturbance in the pipe containing steam ΔV_g, which would be created by the condensation rate $\dot{m}_{gl}$ can be given by

$$\Delta V_g = \dot{m}_{gl} / (\rho_g A_p) \quad (1)$$

where $\dot{m}_{gl}$, ρ_g and A_p are the condensation rate, steam density and flow path area of the pipe, respectively.

The steam condensation rate $\dot{m}_{gl}$ depends on the rate at which pipe wall area becomes available as steam pushes the water column ahead of it, the pipe temperature, and the steam properties. A range of condensation heat transfer coefficients could be obtained, depending on properties of the condensate film growing on the inner wall of the condenser tubes and on the inner wall of the vertical pipe connected to the PCHX.

This velocity disturbance could impose a decompression disturbance. It can be calculated from the waterhammer equation [2] as,

$$\Delta P = \rho_g C_g \Delta V_g / g_0 \quad (2)$$

The decompression disturbance would also propagate into the condensate water region with a velocity disturbance ΔV_l. It can also be estimated from the waterhammer equation as,

$$\Delta V_l = g_0 \Delta P / \rho_l C_l \quad (3)$$

where C_l, ρ_l, and ΔP respectively are the sound speed in water, water density, and decompression disturbance.

2.3 Preliminary Assessment of the PAFS design

Using the rapid condensation-induced waterhammer analysis model presented above, a preliminary calculation of the magnitudes of the decompression and velocity disturbances was performed for an arbitrary range of the geometrical and operational parameters of the PAFS. Some typical results are illustrated as follows.

The steam condensation heat transfer coefficient on the inside the PCHX tube measured at the separate effect test facility [3] ranges between 10,000-30,000 $W/m^2{-}^oK$, depending on the associated fluids and tube material thermal properties.

At the steam pressure P =75 bar, T_{sat} =290.5 ^oC, ρ_g =39.5 kg/m^3, ρ_l =731.0 kg/m^3, h_{gl} =1471.0 kJ/kg, $C_g \approx 488 m/s$, and $C_l \approx 1{,}372 m/s$, T_{sat} and h_{gl} are the saturation temperature and latent heat, respectively. These data with the geometrical dimensions of the PCHX tubes are used in the preliminary calculation.

Figures 2 and 3 respectively show the effects of the initial tube and pipe wall temperature T_w on the disturbances ΔP and ΔV_l for the case where the steam condensation heat transfer coefficient is assumed to be 30,000 $W/m^2{-}^oK$.

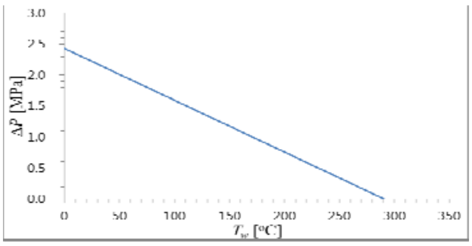

Fig. 2 Effect of T_w on the pressure disturbance ΔP.

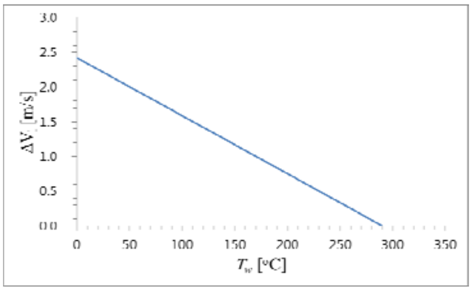

Fig. 3 Effect of T_w on the velocity disturbance ΔV_l in the condensate water.

When the initial temperature of the tubes and pipe is very lower than the steam saturation temperature, a very high decompression disturbance would be caused by the rapid condensation, which could create a significant transient longitudinal force on pipe segments containing water.

3. Conclusions

A simple approach for assessing the potential waterhammer due to rapid condensation in the condensate line of the APR+ PAFS has been provided. The effects of initial condensate pipe wall temperature on the magnitudes of decompression and velocity disturbances have been investigated. The approach and related technical information can be used to perform the safety evaluation of the APR+ PAFS.

REFERENCES

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