Instability Analysis on PRHRS of SMART-P using D-Decomposition Method

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1. Introduction

Passive Residual Heat Removal System (PRHRS) removes the core decay heat and sensible heat by natural circulation in case of an emergency such as unavailability of feedwater supply or loss of off-site power. The PRHRS consists of 4 independent trains with 50 % capacity each. Two trains are sufficient to remove the decay heat. The each train is composed of a Heat eXchanger (HX) submerged in the Refueling Water Tank (RWT), fail-open valves, and a Compensating Tank (CT). Figure 1 shows a schematic diagram of PRHRS.

The CT with water and gas margin is connected to the water intermediate circuit (between SG and HX) by means of pipeline with orifice. The fluid circulation in the intermediate circuit is assured by weight difference of hydrostatic column in its riser and downcomer sections, which creates positive motive head of natural circulation. Availability of two compressible volumes in the intermediate circuit (steam one formed by steam regions of the intermediate circuit and gas one in the form of gas reservoir in the CT) and SG operation under low flow rate with relatively high hydraulic resistance of steam line may induce fluctuating circulation instability. Simple analytical model for the PRHRS instability was developed and impacts of design parameters on instability occurrence were studied in this paper.

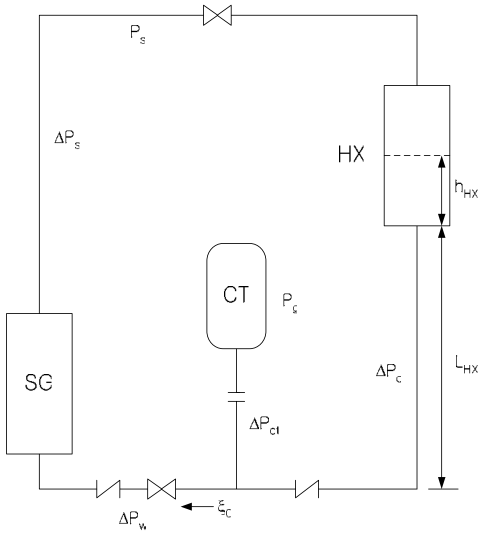

Figure 1. Schematic diagram of PRHRS

2. Analytical Models

Fluctuating instability of PRHRS intermediate circuit is mainly due to steam generation retardation in the SG and dynamic interaction of gas and steam pressurizers.

Steam flowrate at SG outlet is determined by water flowrate at its inlet with a lag for a period of passing economizer section τ_{ec}.

$$\xi_s(t) = \xi_w(t-\tau_{ec}) \tag{1}$$

Fluid mass balance in intermediate circuit (without CT) determines steam pressure in it with a lag τ_{circ}.

$$\tau_s \cdot {}^{d\boldsymbol{P}_s(t)}/_{dt} = -\xi_{ct}(t-\tau_{circ}) \tag{2}$$

Gas mass balance in CT determines gas pressure variation in the differential form.

$$\tau_g \cdot {}^{d\boldsymbol{P}_g(t)}/_{dt} = \xi_{ct}(t) \tag{3}$$

Momentum equations for the CT-SG path and intermediate circuit have following forms

$$a_{ct}\cdot\xi_{ct}(t)=\boldsymbol{P}_s(t)-\boldsymbol{P}_g(t)-a_s\cdot\xi_w^2(t-\tau_{ec})-a_c\cdot\xi_c^2(t)+H_{nc0} \tag{4}$$

$$a_w\cdot\xi_w^2(t) + a_s\cdot\xi_w^2(t-\tau_{ec}) + a_c\cdot\xi_c^2(t) = H_{nc0} \tag{5}$$

and continuity equation (balance of flowrates in the point of CT connection to the circuit)

$$\xi_{ct}(t) = \xi_c(t) - \xi_w(t)\_ \tag{6}$$

In above equations the following designations are used.

$\boldsymbol{P}_j(t)$: relative pressures $(P_j = {}^{P_j}/_{P_j^0})$, s–steam, g–gas

ξ_j : relative flowrates $(\xi_j = {}^{G_j}/_{G_j^0})$, w–water, s–steam, c–condensate, ct–compensating tank

H_{nc0} : relative motive head, $(L_{hxc}+h_{hxc}) / P_{steam}^0$

a_j : relative hydraulic losses $\Delta P_j/P_n^0$, where ΔP_j is hydraulic losses at corresponding sections

τ_j : time constants of steam and gas compressible volumes,

$$\tau_s = {}^{P_s^0}/_{(G_j^0 \cdot {}^{dP_s}/_{dm_f})},\quad \tau_g = (V_g\cdot P_s^0\cdot {}^{d\rho_g}/_{dP_g}\cdot {}^{\gamma_w}/_{\rho_g})/_{G_j^0}$$

Derivative ${}^{dP_s}/_{dm_f}$ is determined on the basis of static dependency and derivative ${}^{d\rho_g}/_{dP_g}$ – based on equation of ideal gas condition. Parameter τ_{ec} means the time for working fluid passage through SG economizer area. Its value may be obtained by dividing water mass in economizer area by flowrate through intermediate circuit

D-decomposition method is used for better understanding during analysis of the system stability, where a coefficients space of the obtained characteristic equation is divided into stable and unstable areas [1]. After linearization of equations (1)~(5) and their Laplace conversion, the following characteristic equation is obtained:

$$s \cdot [a_{ct} C + 2\xi_0 a_c a_w] + C \cdot (\tau_s^{-1} e^{-s\tau_{ec}} + \tau_g^{-1}) = 0 \qquad (7)$$

Where $C = a_w + a_s e^{-s\tau_{ec}} + a_c$

At $a_t \rightarrow \infty$, i.e. at the CT isolation from the circuit, equation (7) is reduced to the following

$$(a_w + a_s \cdot e^{-s\tau_{ec}} + a_c) \cdot s = 0 \qquad (8)$$

It determines the conditions of overall-circuit circulation stability (by steam generation retardation mechanism) in accordance with evident correlation

$$a_w + a_c > a_s \qquad (9)$$

with resonance frequency at the stability boundary $\omega=\pi/\tau_{ec}$. This criterion requires that for the stable operation, hydraulic resistance of the circuit “on water side” should be higher than resistance “on steam side,” if there is no CT.

In a general case the resistance is $a_{ct} < \infty$. Putting $s = j \cdot \omega$, where ω – circular frequency and $j = \sqrt{-1}$, from equation (4.9) after separation of actual and imaginary parts, two parametric equations are obtained for two parameters τ_s^{-1} and τ_g^{-1} characterizing “rigidity” of compressible volumes.

$$\tau_s^{-1} = \frac{x[B(a_{ct}B + 2\xi_0 a_c a_w) + a_s a_{ct} a_c \sin^2 x]}{\tau_{ec} \sin x (B^2 + a_s^2 \sin^2 x)}$$

$$\tau_g^{-1} = \frac{-x[2\xi_0 a_c a_w (B\cos x - a_s \sin^2 x) + a_{ct} a_c a_s \cos x \sin^2 x]}{\tau_{ec} \sin x (B^2 + a_s^2 \sin^2 x)} - \frac{x[a_{ct} B^2 \cos x + a_{ct} B \sin^2 x (a_c - a_s)]}{\tau_{ec} \sin x (B^2 + a_s^2 \sin^2 x)}$$

Where $x=\omega \cdot \tau_{ec}$, $B = a_w + a_s \cos x + a_c$ (10)

and also equation of singular line (at s=0):

$$\tau_s^{-1} + \tau_g^{-1} = 0 \qquad (11)$$

3. Results

Figure 2 present the analysis results of stability boundary in plane of parameters τ_s^{-1} and τ_g^{-1} and characteristics of the SMART-P PRHRS. The stability areas are located to the left from boundary curves. The figure indicates positions of working points with various gas volumes in CT. In analysis of working point positions in parameter plane τ_s^{-1} and τ_g^{-1}, the gas volume in CT varied from 1.25 %V_{ct} to 20 %V_{ct}. The analysis of obtained results shows that the instability caused by dynamic interaction of pressurizers is promoted by reduction of gas pressurizer rigidity (achieved when gas volume in CT increases) and reduction of relative hydraulic resistance, R_{ct}.

4. Conclusion

Simple analytical model for the PRHRS instability was developed by introducing D-decomposition method and impacts of design parameters such as gas volume in CT and hydraulic resistance were studied.

REFERENCES

[1] Dragoslav D. Siljak, *Nonlinear System-The parameter Analysis and Design*, John Wiley & Sons, Inc. 1969.

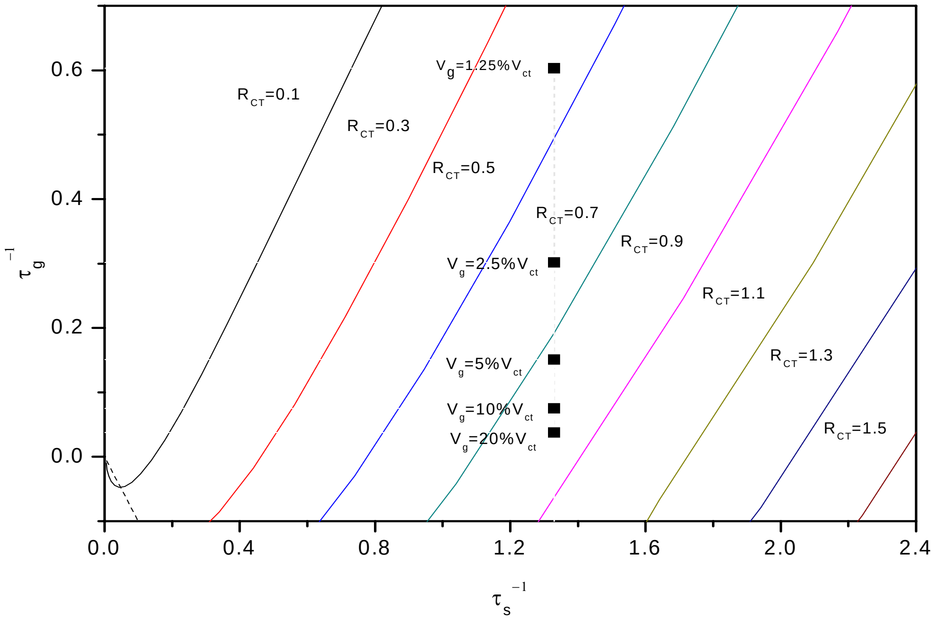

Figure 2. Stability boundary in plane of parameters τ^{-1}_s and τ^{-1}_g