Parameter Study of the Passive Residual Heat Removal System Flow Instability

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1. Introduction

The PRHRS of SMART-P removes the core decay heat and sensible heat by a natural circulation of the two-phase fluid in the case of emergency events such as the unavailability of feedwater supply or loss of off-site power. The PRHRS consists of four independent trains with a 50 % capacity each. Each train includes a Heat eXchanger (HX), fail-open inlet/outlet isolation valves, and a Compensating Tank (CT) [1]. Two-phase condition is ensured for most of the operating time, which guarantees a high efficiency of the heat removal from the primary circuit, with a sufficient enough reserve of the SG heat-exchange surface.

The objectives of this study are to develop convenient analytical tools for the aperiodic and fluctuating instabilities, and to evaluate the effect of each PRHRS design parameter on the system stability. First, a static model for the aperiodic instability using the system hydraulic loss relation and the downcomer feedwater heating equations is developed. The system hydraulic loss is expressed as a function of feedwater flow rate and a portion of the orifices operating in the water mode. Second, a dynamic model for the fluctuating instability owing to a steam generation retardation and a dynamic interaction of two compressible volumes is formulated. D-decomposition method is applied after a linearization of the governing equations.

2. Aperiodic Instability

In the PRHRS, the steam and feedwater nozzles are located above the SG cassettes, which is partially for the elimination of a lower penetration of the vessel and partially for an easier routing of the feedwater pipes. This design feature inevitably requires a little longer feedwater module pipe submerged in the primary coolant, which brings about a feedwater preheating in front of the tube orifices. For the rated condition, a temperature rise of the feedwater through the feedwater module pipe is confined within the design limit, while the value will be significant enough for the low flow condition, especially for the PRHRS operating mode.

For a quantitative evaluation of the aperiodic instability, it is required to use an analytical model which takes into account a branching of the circuit into two downcomer sections in the SG, one operating in the water mode and the other operating in the steam mode.

Corresponding mathematical model of the intermediate circuit thermo-hydraulics includes two balance equations between the motive head and hydraulic losses. One is for the circuit and the other for the equivalent downcomer sections:

$$(L_{HX}+h_{HX})+h_{SG}\times 1(a)=\left\{\Delta P^0_{steam}\left(\frac{\gamma^0_{steam}}{\gamma_{steam}}\right)+\Delta P^0_{water}\right\}\xi^2_{circuit}+\frac{\Delta P_{water}}{a^2}\cdot|\xi_{water}|\cdot\xi_{water} \quad (1)$$

$$h_{SG}\times 1(a)=\frac{\Delta P_{water}}{a^2}\cdot|\xi_{water}|\cdot\xi_{water}-\frac{\Delta P_{steam}}{(1-a)^2}\cdot|\xi_{steam}|\cdot\xi_{steam} \quad (2)$$

Feedwater heating through the steamed and water module pipes of a SG are expressed as follow:

$$I_{water}=I_{SGinlet}+\frac{U_{orifice}\cdot a\cdot\{T_{1C}-(T_{water}+T_{SGinlet})/2\}}{G^0_{SG}\cdot\xi_{water}} \quad (3)$$

$$I_{steam}=I_{SGinlet}+\frac{U_{orifice}\cdot(1-a)\cdot(T_{1C}-T_{steam})}{G^0_{SG}\cdot\xi_{steam}} \quad (4)$$

When varying a portion of the orifices operating in the water mode, a (within range [0,1], including a=0 and a=1), a hydraulic curve of the circulation circuit can be expressed in the following form:

$$(L_{HXC}+h_{HXC})=F(\xi_{circuit},a) \quad (5)$$

Fig. 1 presents the analysis results of equation (5) for the P^0_{steam}=3MPa, $T_{SGinlet}$=150°C. The required parameters for this analysis are obtained from the steady state design program, which calculates the PRHRS state variables from the given primary and environmental conditions [1]. From Fig. 1, it can be seen that with the assigned value of the motive head $(L_{HX}+h_{HX})$ in the area restricted by the curve, $F(\xi_{circuit}, a=1)$ for the flowrate of $\xi_{circuit}>\xi_{bound}^{100\%}$ and by the curve, $F(\xi_{circuit}, a=0)$ for the flowrate of $\xi_{circuit}<\xi_{bound}^{0\%}$, there can be many possible operational states which are different from each other by a portion of the orifices operating in the water mode, a.

Fig. 1 also shows the curve $F(\xi_{circuit}, a_{probable})$, along which there is no flowrate through the steamed module pipes. If we assume that the flowrates for the steamed module pipes are zero, then equation (1) is simplified as follows:

$$F(\xi_{ciruit},a_{probable})=\left\{\Delta P^0_{steam}\left(\frac{\gamma^0_{steam}}{\gamma_{steam}}\right)+\Delta P^0_{water}\right\}\xi^2_{circuit} \quad (6)$$

Equation (6) shows that the circuit flowrate does not depend on the SG pressure drop characteristics. If $a<a_{probable}$, then the flowrate through the steamed feedwater module pipes is positive.

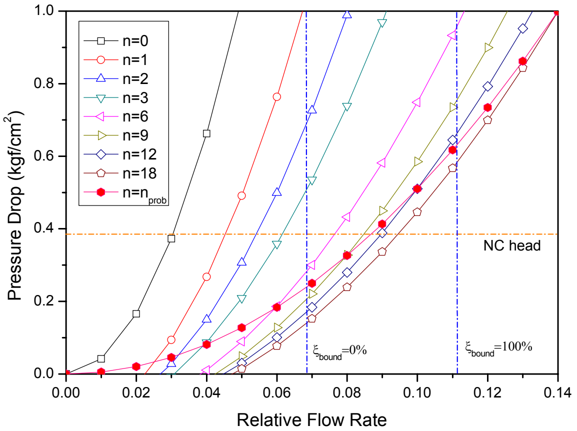

Fig. 1. Hydraulic Curves, $F(\xi_{bound}, a)$ for the Various a Values

Due to their relatively larger frictional loss, the flowrate of the steamed module will be decreased and a approaches $a_{probable}$. On the contrary, if $a > a_{probable}$, then the flowrate through the steamed feedwater module pipes is negative. In this situation, steam is mixed with the feedwater in the feedwater module header, which will disturb the operation of the non-steamed module pipes and as a consequence, a again approaches $a_{probable}$. In the real situation, the value, a is thought to fluctuate around $a_{probable}$.

3. Fluctuating Instability

The fluctuating instability of the PRHRS is mainly by a dynamic interaction of two compressible volumes and a retardation mechanism of steam generation in the SG, so the governing equations for the instability analysis are derived by focusing on these two phenomenal characteristics. An analytical model is developed with the variables which are intentionally defined for taking into account the existence of two compressible volumes and a retardation of steam generation in the SG.

D-decomposition method is used for a better understanding during an analysis of the system stability, where a coefficients space of the obtained characteristic equation is divided into stable and unstable areas [2]. After a linearization of the governing equations 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 $C=a_w+a_s e^{-s\tau_{ec}}+a_c$

Putting $s=j\cdot\omega$ from equation (7) after a separation of the actual and imaginary parts, two parametric equations are obtained for two parameters τ_s^{-1} and τ_g^{-1} characterizing the rigidity of the compressible volumes.

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

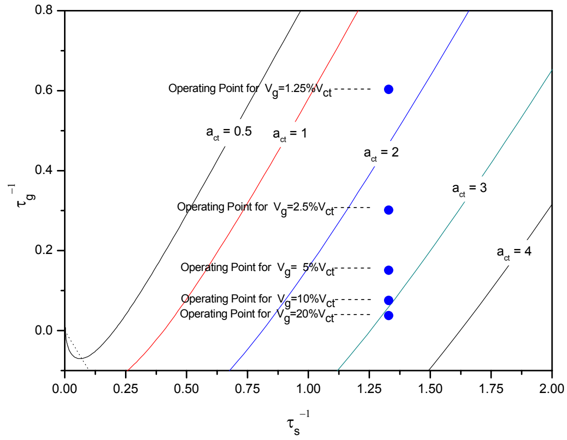

Fig. 2. Stability Boundary in Plane of Parameters τ^{-1}_s and τ^{-1}_g for the Fixed Operating Pressure

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

where $x=\omega\cdot\tau_{ec}$, $B=a_w+a_s\cos x+a_c$ (8)

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

$$\tau_s^{-1}+\tau_g^{-1}=0 \qquad (9)$$

Fig. 2 presents the stability boundary in the plane of the parameters τ_s^{-1} and τ_g^{-1} for the fixed steam pressure. The analysis of the obtained results shows that the instability caused by the dynamic interaction of the pressurizers is promoted by the following:

- Increase of τ_s^{-1} (decrease of steam volume)
- Reduction of τ_g^{-1} (achieved when the gas volume in the CT increases)
- Reduction of the hydraulic resistance of path a_{ct}

4. Conclusions

In this paper, simple and convenient analytical tools for the evaluations of the aperiodic and fluctuating instabilities of the SMART-P PRHRS were developed and the effect of each PRHRS design parameter on the system stability was evaluated.

REFERENCES

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