Numerical Simulation of the Pressure Distribution in the Reactor Vessel Downcomer Region Fluctuated by the Reactor Coolant Pump

Dong Hwa Jeong [*], Byung Ryul Jung, Ho Cheol Jang, Seok Jeong Yune and Eun Kee Kim
[a]*KEPCO Engineering & Construction Company, Inc.,*
989-113, Daedeokdaero Yuseong-gu, Daejeon, 305-353, KOREA
[*]*Corresponding author: dhjeong@kepco-enc.com*

1. Introduction

In this study the numerical simulation of the pressure distribution in the downcomer region resulting from the pressure pulsation by the Reactor Coolant Pump (RCP) is performed using the Finite Difference Method (FDM).

The pump-induced acoustic loads in the OPR1000 and APR1400 designs have been determined by solving the wave equation using an analytical method [1-3]. In a different way, a numerical solution for the wave equation also can improve understanding of the pressure distribution in the downcomer region [4].

This simulation is carried out for the cylindrical shaped 2-dimensional model equivalent to the outer surface of the Core Support Barrel (CSB) of APR1400 and a 1/2 model is adopted based on the bilateral symmetry by the inlet nozzle. The fluid temperature is 555˚F and the forcing frequencies are 120Hz, 240Hz, 360Hz and 480Hz. Simulation results of the axial pressure distributions are provided as the Root Mean Square (RMS) values at the five locations of 0°, 45°, 90°, 135° and 180° in the circumferential direction from the inlet nozzle location.

2. Methods and Results

2.1 Computational Domain

The computational domain is shown in Fig. 1. The axial length of the domain is 410 inches. The distance from the upper boundary to the inlet nozzle interface pressure location is 140 inches. And the outer radius of the CSB is 81.5 inches.

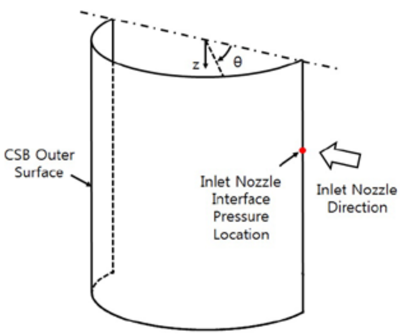

Fig. 1 Schematic Computational Domain

The upper boundary of the domain is the seating surface of the CSB. The inlet nozzle interface pressure is given at the point where the inlet nozzle centerline intesects the outer wall of the CSB. The source of the pressure pulsation is a cosine wave having the arbitrary amplitude of $\sqrt{2}$ psi. If the pressure distribution normalized to the RMS value of 1 psi is multiplied by the actual RMS values of inlet nozzle interface pressure, actual pressure distributions can be obtained. To obtain the pressure distribution normalized to 1 psi, the distribution is divided by the inlet nozzle interface pressure.

2.2 Governing Equation

The coolant temperature in the whole domain is constant and is set to be the same as the inlet nozzle temperature. The acoustic wave equation of the cylindrical coordinate system is as follows.

$$\frac{\partial^2 p}{\partial t^2} = c_0^2\left(\frac{\partial^2 p}{\partial z^2} + \frac{\partial^2 p}{r^2 \partial \theta^2}\right) + S$$

Here, p is the pressure fluctuation and c_0 is the sonic velocity of 40065 inch/sec for 555˚F and 2,250 psi condition. t is time. z and θ are the axial and circumferential coordinates, respectively. r is the outer radius of the CSB. S is a source term.

2.3 Numerical Method

The FDM is used to solve the wave equation. The 2nd order central difference scheme is applied to spatial derivatives and the explicit scheme is applied to time derivative. A total of 98,400 elements are used (410 elements for the axial direction and 240 elements for the circumferential direction). The CFL number is 0.5. The boundary conditions are as follows.

$p = 0$ for the lower boundary
$\partial p/\partial z = 0$ or $\partial p/\partial \theta = 0$ for other boundaries

The pressure is assumed to be symmetrical on both boundaries in the circumferential direction.

2.4 Results

The temperature condition is 555˚F, which is the cold leg temperature during normal operation. For the frequencies of 120Hz, 240Hz, 360Hz and 480Hz, which are all multiples of the Blade Passing Frequency (BPF) of the RCP, the pressure distributions in the downcomer region are calculated. When determining the pump-induced acoustic loads, 20Hz and 40Hz frequencies are also considered. The two frequencies are the multiples of the RCP rotation speed. However, the pressure pulsations at those frequencies seem not to be of acoustic origin.

As a result, the axial pressure distributions at the 5 circumferential locations in Fig. 2 are given as the RMS values. The physical time for the simulation is 5 minutes and after that, the data for 5 seconds are analyzed to obtain the RMS values.

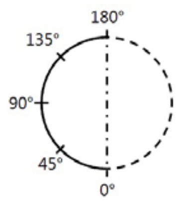

Fig. 2 Locations for the Result Data

Fig. 3 shows the axial pressure distributions at the 0° location for all frequency conditions. The maximum value for each frequency ranges from 2 psi to 2.5 psi. The number of waves obtained in the axial direction increases at high frequencies. The variations of the waves at the 120Hz and 360Hz frequencies are relatively larger compared to those at other frequencies.

In Fig.3, cuspidate points are shown on the inlet nozzle interface pressure location for all frequency conditions. It seems that the interference of waves returned from the upper and lower boundaries and the source of sinusoidal wave results in the unpredictable value which prevents smooth connection of the returned waves. In particular, for the peak value at the 120Hz frequency, the interference of the waves returned from both boundaries makes relatively large amplitude compared to at the other frequencies.

Figs. 4 ~ 7 show the axial pressure distributions for frequencies of 120Hz, 240Hz, 360Hz and 480Hz as RMS values normalized to 1 psi. The maximum pressure near the seating surface of the CSB is about 20% larger than the inlet nozzle interface pressure except for the 120Hz frequency condition. Accordingly, if the pressures on both sides of the CSB (e.g. 0° and 180° locations) are considered, the upper part of the CSB can be affected by the pressure that is 2.4 times higher than the measured pressure at the inlet nozzle interface pressure location. The maximum pressure seems to be caused by superposition of waves reflected from the seating surface and waves newly arrived from the inlet nozzle interface pressure location.

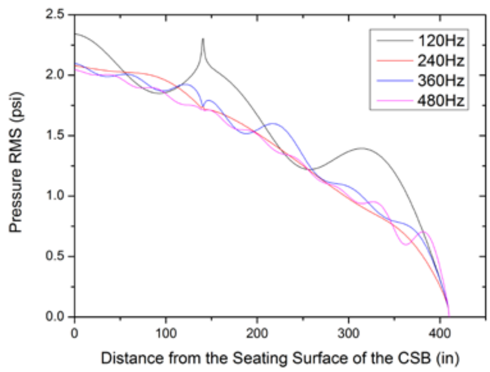

Fig. 3 Axial pressure distribution at 0° location

3. Conclusions

In the study, the numerical simulation of pressure distributions in the downcomer region induced by the RCP was performed using FDM and the results were reviewed.

The interference of the waves returned from both boundaries in the axial direction and the source of the sinusoidal wave is shown on the inlet nozzle interface pressure point.

The maximum pressures occur in the upper part of the CSB, which can be affected by the pressure that is up to 2.4 times higher than the measured pressures at the inlet nozzle interface pressure location. It seems that the maximum pressures result from the superposition of the waves reflected from the seating surface and the waves newly arrived from the inlet nozzle interface pressure location.

In further study, the numerical solutions obtained in this simulation will be compared to an analytical solution for the same model.

REFERENCES

[1] L. Lee, Pump-induced fluctuating pressure in a reactor coolant pipe, International Journal of Pressure Vessels and Piping, Vol. 8(6), pp.407-417, Nov., 1980

[2] K. B. Lee, I. Y. Im and S. K. Lee, Analytical Prediction on the pump-induced pulsating pressure in a reactor coolant pipe, International Journal of Pressure Vessels and Piping, Vol.52(3), pp.417-425, Jan., 1992

[3] K. B. Lee and I. Y. Im, An analytical study on the pump-induced acoustic pressure in a pressurized water reactor, Nuclear Engineering and Design, Vol.147(3-147), pp.275-286, Apr., 1994

[4] Dean G. Duffy, Advanced Engineering Mathematics, CRC Press, 1997

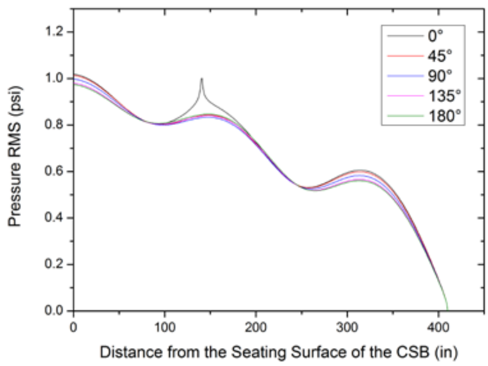

Fig. 4 Axial pressure distribution for 120 Hz frequency

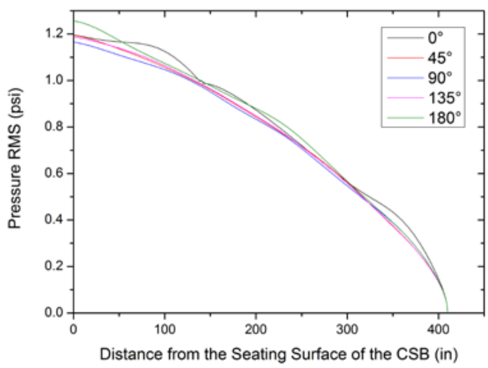

Fig. 5 Axial pressure distribution for 240 Hz frequency

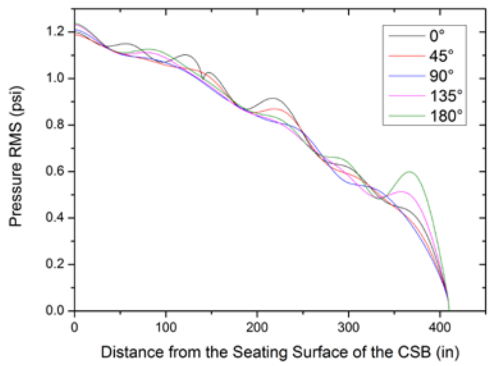

Fig. 6 Axial pressure distribution for 360 Hz frequency

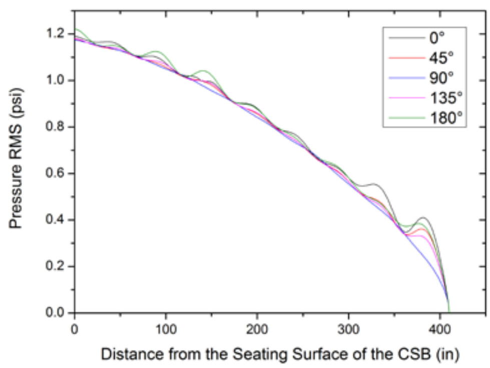

Fig. 7 Axial pressure distribution for 480 Hz frequency