A Study on Critical Water Level during Mid-Loop Operation

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1. Introduction

Recently much concern has been increasing that an event involving the loss of decay heat removal while substantial core decay heat may pose a significant likelihood of a release due to a severe core damage accident [1]. Especially during the mid-loop operation mode, the loss of the shutdown cooling can challenge the reactor safety.

A significant phenomenon associated with the mid-loop operation is air or gas entrainment into the suction line of the shutdown cooling system (SCS) due to free surface vortex. To address this problem, NRC presents acceptance criteria based on Froude Number [2]. Also Westinghouse did some experimental works and established a correlation between critical water level and vortex occurrence [3].

This paper proposes acceptance criterion on the critical water level to vortex formation in the SCS suction line based on Vortex-Froude number correlation derived from Computational Fluid Dynamic (CFD) analyses. An analysis tool is STAR CCM+.

2. Methods and Results

2.1 Geometry data

Analysis geometry is shown on figure 1. An inlet is a hot leg nozzle connected to the reactor vessel and an outlet is located approximately 1.0 m below the SCS suction line that is connected to the bottom of the hot leg. RCS water introduced from the inlet flows through SCS suction line. During the mid-loop condition hot leg is filled with RCS liquid water and air with a free surface. Nozzle dam is installed on the steam generator side to prevent an overflow of RCS water to a steam generator. Symmetric geometry is applied in this analysis for an analytical convenience.

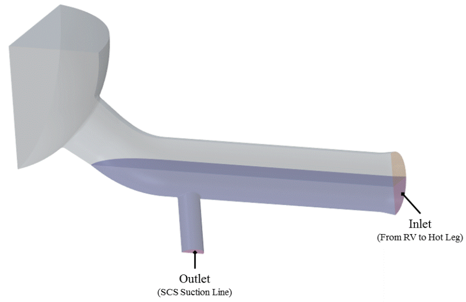

Figure 1 Geometry of Hot Leg for CFD analysis

2.2 Modeling data and methods

Two conditions in this analysis are selected as Case 1 and Case 2. These cases depend on SCS operating conditions. Input data is summarized in table I.

An automated mesh generation is used by polyhedral and prism layer meshes. The inlet and outlet boundary conditions are velocity inlet. The inlet and outlet velocity are an average velocity at each section calculated by total flow rates. The air region of inlet is stagnation inlet. The physics model is volume of fluid (VOF), isothermal and K-ε turbulence model.

Table I: Input data for analysis

	Case 1	Case 2
RCS Flow Rate , [*l*/m]	15,709	9,000~ 17,000
RCS Water Level [m]	0.4064 ~ 0.5842	
Temperature [^{o}C]	57.2	26.5~29.7

2.3 Analysis results

The typical analysis result is shown on figure 2. The left side part of figure 2 is the front view of symmetric plane and red part shows free water surface. The RCS water level, RCS mass flow rate and minimum water level of free surface are depicted on the right side of figure 2. While the RCS mass flow rate and RCS water level are nearly stable during the simulation, minimum water level of free surface is unstable at an initial stage but stable at an sufficient simulation time elapsed.

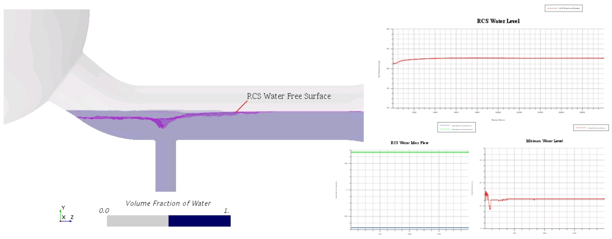

Figure 2 Analysis results with a vortex generation on free surface (water level: 0.5334 m for Case 1)

The velocity and vorticity of free water surface are shown on figure 3. The upper left part of figure 3 shows the free surface velocity. The result shows that velocity is increased gradually from inlet to SCS suction line. However the region between the SCS suction line and steam generator is stagnant. The velocities range up to 42% of an inlet (average velocity).

The vorticity of free water surface is shown on the bottom right part of figure 3. The vorticity of a suction direction is developed at the vortex near the entrance to suction pipe. Therefore the vortex is defined by the vorticity which is the same direction as a suction flow.

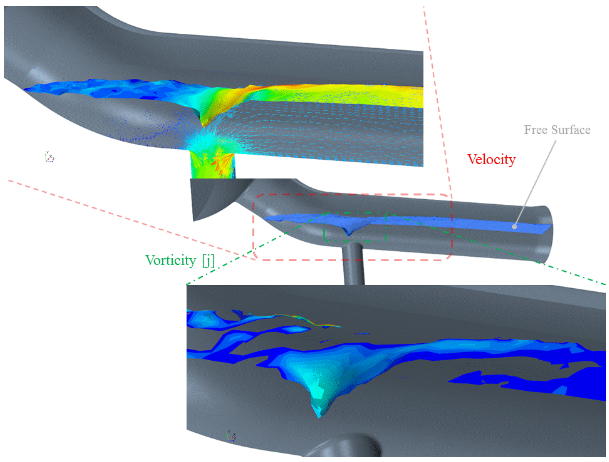

Figure 3 Velocity and vorticity on the free surface

2.4 Comparison of analysis results

The CFD results for Case 2 are shown together with test results on figure 4. The x-axis is total flow rate and the y-axis is a deviation from hot leg centerline. The curves represent a critical water level where vortex can be formed at the SCS suction line. The red and blue lines show test results for different SCS pump operation condition. The green line shows a critical water level derived from the CFD results which are a little higher water level for vortex formation compared with the test results.

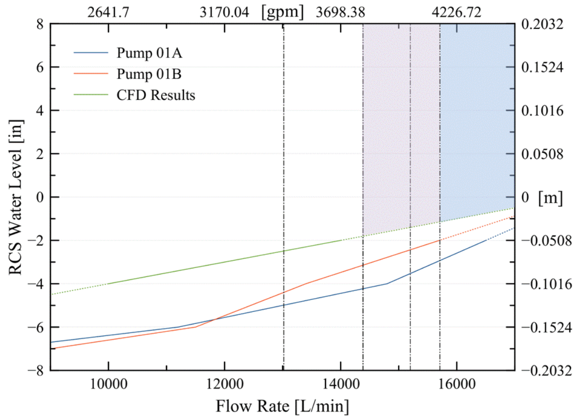

Figure 4 Comparison of test and analysis results for Case 2

2.5 Analysis of Vortex formation by Froude Number

The typical critical water level for vortex formation is described by the following equation [4]:

$$\frac{H_c}{d} = aFr^b \qquad (1)$$

Where, H_C is the critical water level, d is diameter, Fr is Froude number, a and b are constants.

H_C is a water level where vortex formation could be expected to start and d is suction pipe diameter, Fr is a Froude Number. This equation shows that H/d is proportional to Froude number. In theoretical study b is 0.5 [5] but several experiments show that b ranges 0.14 to 0.68 [6].

The Froude number is defined using process average values by the following:

$$Fr = \frac{V_M}{\sqrt{gD}} \qquad (2)$$

Where, V_M is the mean velocity in horizontal pipe, g is gravity and D is diameter of suction pipe.

In this study, Vortex-Froude number is proposed and defined by the following:

$$Fr = \frac{V_V}{\sqrt{gD}} \qquad (3)$$

Where, V_V is the mean velocity in vortex section where the vorticity is the same direction as a suction flow.

The correlation between Froude number and H/d is shown on figure 5. The red and blue lines represent the results calculated by mean Froude number and Vortex-Froude number respectively. Also the green line shows NRC guidance for critical water level [2]. The results for Case 2 are plotted on the figure for comparison.

The red and blue regions are a stable operational range derived from mean Froude number and Vortex-Froude number of the vortex section, respectively. It is noted that two test data are located near the curve derived from mean Froude number, but essentially not within the curve (blue region) with Vortex-Froude number curve (blue region). This shows that the acceptance curve derived from the Vortex-Froude number can be used as guidance for a stable operational range without gas intrusion into the suction piping.

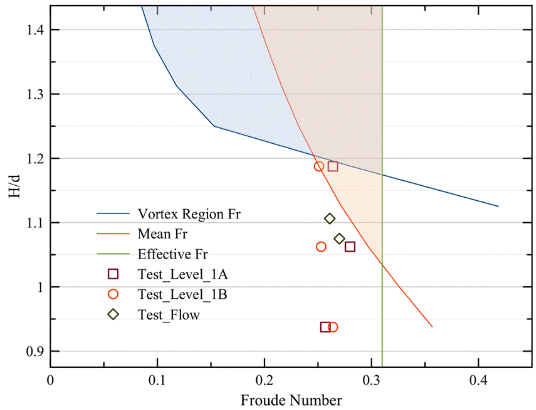

Figure 5 Correlation between Froude number and H/d

3. Conclusions

Several correlations have been proposed for a critical water level where vortex could be expected to start and grow. Those are based on experimental and theoretical analysis results, which are basically represented using Froude number and H/d parameters. The used Froude number is based on process average values regardless of vortex formation.

The proposed acceptance curve for critical water level based on Vortex-Froude number can be used as a preliminary guidance for air intrusion into the suction pipe. Also it is noted that the proposed curve shows a little more conservative limit for a critical water level to be on a safer operation during the mid-loop operation.

REFERENCES

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