A Numerical Analysis Study to Identify the Leak Cause of Feedwater Heater Vent Pipe in CANDU Plant

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Abstract

Piping installed in nuclear power plants is affected by various degradation mechanisms and may be ruptured after being gradually thinned. The degradation mechanisms such as flow-accelerated corrosion (FAC), cavitation, liquid droplet impingement erosion (LDIE), etc., can lead to costly outages and repairs, resulting in plant reliability. In August 2008, the header pipe in the high pressure feedwater heater vent system was leaked at a Korean CANDU nuclear power plant. As the result of inspection after cutting the pipe, it was identified that the leak was evoked due to LDIE. This paper presents the numerical analysis result using ANSYS FLUENT for the purpose of identifying the cause of the leak, the comparison results of the wear rate based on the both the existing evaluation models and the measured thickness data.

1. Introduction

The major cause of wall-thinning damages that occur in nuclear power plant piping has been known as Flow-Accelerated Corrosion (FAC). After the pipe rupture accidents caused by FAC occurred in US Surry nuclear power plant in 1987, many studies have been made to manage the FAC for pipes and equipment in nuclear and fossil power plants. A considerable number of nuclear utilities around the world have operated FAC management program based on the study such as CHECWORKS and COMSY Program.

But, many wall-thinning caused by other mechanisms such as cavitation, flashing, solid particle erosion and liquid droplet impingement have frequently occurred in nuclear power plant piping. In the middle of the mechanism, Liquid Droplet Impingement Erosion (LDIE) is regarded as one of the major unpredictable aging mechanisms occurred in plant pipe. Therefore, evaluating LDIE of inner pipe wall is the important aging issue in the nuclear power plant pipe. However, the exact causes of LDIE mechanism occurred in nuclear piping systems are not fully identified yet [1].

In 2008, the feedwater heater vent pipe in Korean CANDU nuclear power plant occurred a leakage during the operating period. According to the result of destructive examination for the leaked vent pipe, it isestimated that the LDIE is the main cause of the leakage. The purpose of this study is to identify the main cause and phenomenon for the leakage ofvent pipe through the numerical flow analysis. The theoretical model wear rate calculated using the parameters obtained from numerical flow analysis are compared with the wear rate calculated from wear value measured from the leaked pipe.

2. Design, operating condition and damage characteristics

2.1 Design and operation condition

A schematic diagram for the leaked feedwater heater vent pipe of Korean CANDU nuclear power plant is shown in Figure 1. The location of the leaked pipe is described as the dotted circle in the Figure1.The vent pipes of 2-inch are connected to 6-inch header pipe. The vent pipes of 2-inch equipped with orifices are made of carbon steel, and normal operating condition.

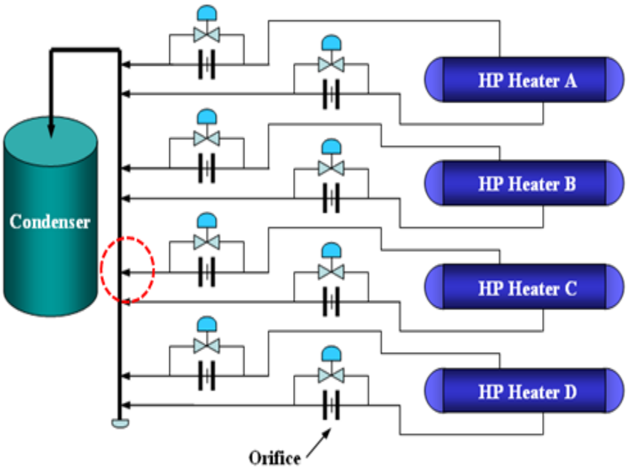
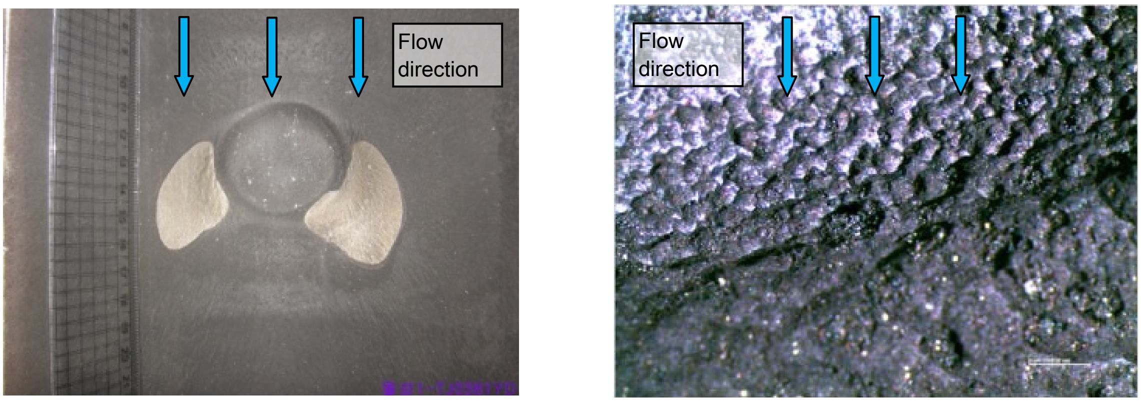


Figure 1System Schematic Diagram

2.2 Characteristics of damage

The damaged part of 6-inch header pipe is shown in Figure 2. An overview picture on the leaked pipe surface is presented in Figure 2(a), wherein the formed magnetite is also observable. The brighter parts on the leaked pipe surface in the Figure 2(a) show that the pipe material is exposed due to the liquid droplet impingement erosion. The microscopic picture on the leaked pipe surface is shown as Figure 2(b), where the small craters,being the typical ageing pattern of LDIE, are also shown clearly.



(a) (b)

Figure 2 Configuration of degraded surface

3. Model configuration and numerical flow analysis results

3.1 Composition and boundary condition of numerical model

To analyze the exact reason for the leaked phenomenon, numerical flow analysis is performed using FLUENT commercial code for leaked pipe systems, while GAMBIT program is used for the generation of mesh.Figure 3 shows the grid system using hybrid methods. Based on the results of sensitivity analysis, approximately 600,000 cells are used. Standard k-ε model is adapted as turbulent viscosity model. The orifice as shown in Figure 1 is excluded from the analysis model because it is located at 20D(diameter) distance from the header pipe.In addition, the bypass line in the branch pipe is also excluded from the model because it is blocked during normal operation. The inlet and outlet boundary condition values for the analyzed pipe is applied using the analysis result of NFA (Network Flow Analysis) which is one dimensional flow analysis code for CHECWORKSFAC program.

According to the results of NFA, inlet flow velocity fromHP heater A, B vent pipe as shown in Figure 1 is 30.226 m/s and the inlet flow velocity fromHP heater C, D vent pipe is 51.9 m/s. The outlet pressure of header pipe is -50.59 KpaThe flowtemperature is considered to be 100℃,and flow condition is steady-state, two-phaseflow included with liquid droplet.The size of liquid droplet is estimated as 10^{-5}meter.

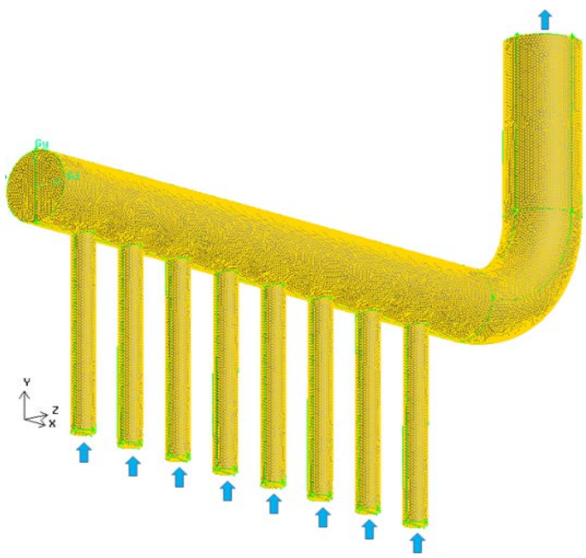


Figure 3Grid system for analysis

The leaked pipe wasoperated at two-phase fluid condition. However,the drag law between phases was not known. Mixture multi-phase model is applied to analysis. The governing equations of mixture multi-phase model are as follows;

Momentum equation

$$\frac{\partial}{\partial t}(\rho_m \vec{\upsilon}_m) + \nabla \cdot (\rho_m \vec{\upsilon}_m \vec{\upsilon}_m) = -\nabla p + \nabla \cdot \left[\mu_m (\nabla \vec{\upsilon}_m + \nabla \vec{\upsilon}_m^{\,T}) \right] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} a_k \rho_k \vec{\upsilon}_{dr,k} \vec{\upsilon}_{dr,k} \right)$$

Energy equation

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\alpha_k\rho_k \mathrm{E}_k)+\nabla\cdot\sum_{k=1}^{n}\left(\alpha_k\vec{\upsilon}_k(\rho_k\mathrm{E}_k+\rho)\right)=\nabla\cdot(k_{eff}\nabla T)+S_E$$

Relative velocity equation

$$\vec{\upsilon}_{dr,p}=\vec{\upsilon}_{qp}-\sum_{k=1}^{n}\frac{\alpha_k p_k}{\rho_m}\vec{\upsilon}_{qk}$$

Volume fraction equation

$$\frac{\partial}{\partial t}(\alpha_p\rho_p)+\nabla\cdot(\alpha_p\rho_p\vec{\upsilon}_m)=-\nabla\cdot(\alpha_p\rho_p\vec{\upsilon}_{dr,p})$$

Where, ρ_m : mixture density

$\vec{\upsilon}_m$:mass-averagedvelocity

p : pressure

μ_m : iscosity of the mixture

$\vec{g}$: cceleration of gravity

$\vec{F}$: bodyforce

n: number of phase

α_k : volume fraction of phase k

p_k :density of phase k

$\vec{\upsilon}_{dr,k}$: drift velocity of secondary phase k

$\mathrm{E}_k =\ h_k$ (incompressible fluid)

h_k :sensible enthalpy for phase k

$\vec{\upsilon}_k$: mean velocity of phase k

k_{eff} : effective conductivity

T: temperature

S_E : volumetric heat source

$\vec{\upsilon}_{dr,p}$: drift velocity of secondary phase p

$\vec{\upsilon}_{qp}$: velocityofasecondaryphaseprelativetothevelocityoftheprimaryphaseq

$\vec{\upsilon}_{qk}$: velocityofasecondaryphase krelativetothevelocityoftheprimaryphaseq

α_p : volume fraction of phase p

ρ_p : density of phase p

3.2 The result of numerical analysis

In the middle of eight vent pipes connected to the header vent pipe, those from the first through the fourth are experiencing wall-thinning damages. Accordingly, the cause of leakage experienced in the fourth pipe is analyzed, and the result is illustrated with the analyzed points as in Figure 4.

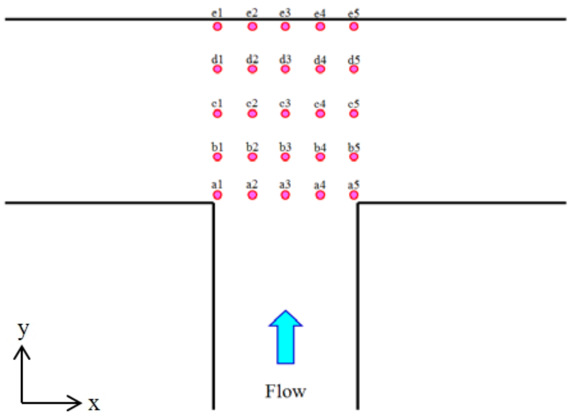


Figure 4Calculation Points

Y-directional velocities in computational analysis for the leaked pipe are shown inFigure 5. Because this study focuses on the analysis for the exact reason of LDIE in leaked pipe, y-directional velocity is only considered for the analysis of the leaked pipe based on the characteristic of LDIE.It is observed in Figure 5 that the first left side vent fluid collides perpendicularly on the inner wall of the header pipethe second vent fluid is bent toward the exit of the headerpipe. It is known that the vent fluid from the fifth to the eighth is too weak to give impact on the wall of the header.

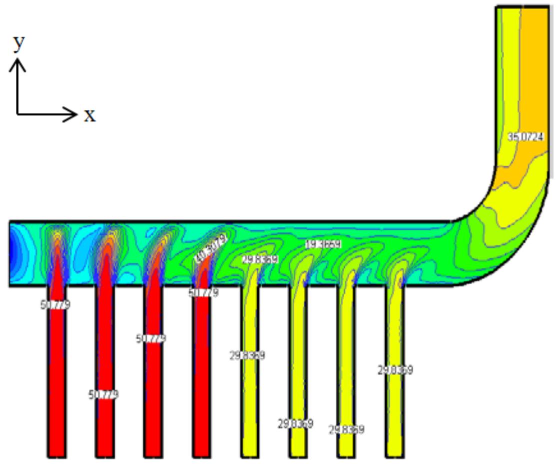
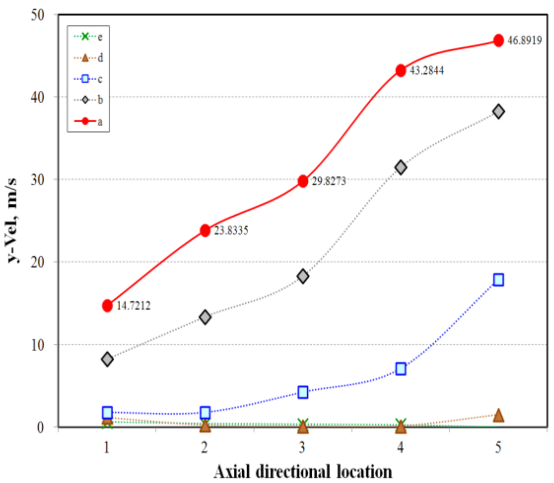


Figure 5 Y-direction liquid velocity distribution

According to the distribution of y-directional fluid velocity as depicted in Figure 5, it is estimated that the header pipe area collided with the first vent fluid shows wall-thinning by erosion.It is, however, the fourth vent pipe connectedto the header, where the most severe wall-thinning occurs.The reason is caused by the operating characteristics of the feedwater heater. The fourth vent fluid flow is bent toward condenser, but we can see the ring-shaped erosion on the inner header pipe wall perpendicular to branch vent pipe. The reason is conjectured that the water inertia force is bigger than vapor inertia force. The velocity distribution of the axial direction to the calculation points as shown in Figure 4 is depicted in Figure6. The results show that it is increasing velocity toward condenser(No. 5),because the pressure at point No. 5 in Figure 6 is lowest due to the condenser. The velocity distribution of the radial direction to header pipe is shown in Figure 7. The results show that the velocity toward on the wall of pipe is rapidly decreasing. Figure 8 shows the static pressure distribution for calculation points.



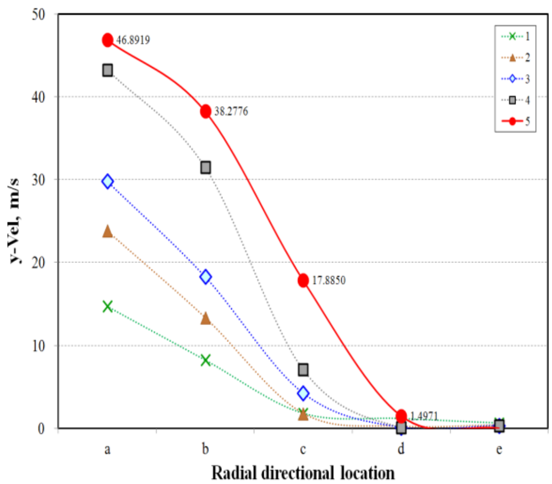


Figure 6 Y-vel. distribution innerheaderFigure 7Y-vel. distribution innerheader
pipe by axial direction locationpipe by radial direction location

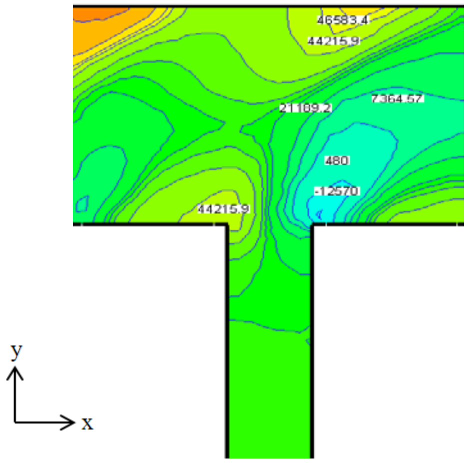


Figure 8 Pressure distribution for calculation points

4. Comparison between the results of LDIE wear rate models

The parameter obtained from the numerical analysis is applied to the theoretical model of LDIE for obtaining the predictive wall-thinning rate.The Sanchez [2] and Heymann model [3] are applied as a theoretical model.The Sanchez LDIE model equation is as follow ;

$$\dot{m} = \frac{C\rho\dot{m}_{tot}(1-x)v_d^t F_e F_h}{(p \in_c)^2 A_c} \quad (1)$$

Where, $\dot{m}$: wear rate per unit area, kg/ m^2hr

C : equilibrium concentration ability of magnetite, kg/m^3

ρ : density of liquid, kg/m^3

$\dot{m}_{tot}$:mass flow rate, kg/hr

x : steamquality, unitless

v_d^t : drop velocity, m/s

F_e :entrainment fraction, unitless

F_h : hitting fraction, unitless

p : indentation hardness, Pa

$\in_c$: oxide critical strain to fracture, unitless

A_c : characteristic area, m^2

$$\dot{m} = 1.4 \times 10^{-12} v_f V_d^{5.047} \quad (2)$$

Where,

v_f : liquid volume, m^3

Applied variables to evaluate are as follows ;

○ Droplet velocity: 46.89m/s (For numerical analysis, the fastest velocity was applied to the middle of vent pipe velocity)

○ Droplet density : 873.87kg/ m^3

○ Vapor density : 6.39kg/ m^3

○ Quality : 0.914

The measured wear rate based on the measured data for the leaked pipe is 0.31mm/yr, and it is 9 times higher than the one of the Sanchez model calculated as 0.028mm/yr.The wear rate based on Heymann model is predicted as 0.41mm/yr which is 1.3 times higher than the measured wear rate.The reason why the wear rate of Heymann model is higher than the measured wear rate is that the Heymann model excessively considersthe velocity of liquid droplet than other parameters such as droplet diameter, frequency of impact, hardness of material, quality, etc., as shown equation (1).The Sanchez model as shown in equation (2) considers many parameters than the Heymann model. However, the Sanchez model also has the limits of analysis, such that it does not consider the droplet size into account.

According to the results of Li's study[4] in 2011, droplet size is related to LDIE erosion. Figure9 shows that droplet size is the affected parameter related to LDIE wear rate. Therefore, the wear rate of the Sanchez model whichdoes not consider the droplet size, is presumed to be non-conservative in determing the wear rate than the measured wear data.

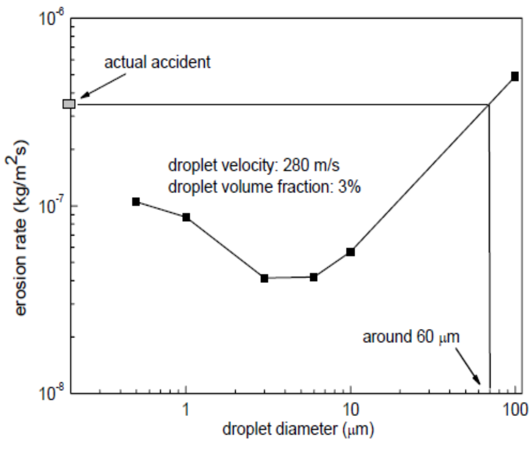


Figure 9Relation between erosion rate and droplet size

Therefore, the existing models for LDIE need to be revised considering several parameters such as droplet size, physical properties of magnetite on the pipe interior, quality, frequency of impact, etc.

5. Conclusion

In 2008, the leakage occurred in the feedwater heater vent pipe in the Korean CANDU nuclear power plant. Based on the result of the inspection on the inner surface of the leaked pipe, the main wall-thinning mechanism is found to be LDIE caused by the annular flow. In order to evaluate the effect of flow in the leaked pipe, numerical analysis is conducted with the leaked pipe.By comparing the wear rates of the Sanchez and Heymann model with the measured wear rates calculated with the leaked pipe,there are significant differences between the measured and the theoretical wear rates. Therefore, further study is necessary to predict the wear rate caused by LDIE, considering several factors such as droplet size, physical properties of magnetite on the pipe interior, quality, frequency of impact, etc.

6. References

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