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A Numerical Study on Flow-Accelerated Corrosion in Two Adjacent Elbows

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Flow-Accelerated Corrosion (FAC) is a well-known degradation mechanism that attacks the secondary piping in nuclear power plants. Since the Surry Unit 2 event in 1986, most nuclear power plants have implemented management programs to deal with damages in carbon and low-alloy steel piping. Despite the utmost efforts, damage induced by FAC still occurs in power plants around the world. In order to predict FAC wear, some computer programs were developed such as CHECWORKS, CICERO, and COMSY. Various data need to be input to these programs; the chemical composition of secondary piping, flow operating conditions and piping geometries. CHECWORKS, developed by the Electric Power Research Institute (EPRI), uses a geometry code to calculate geometry effects. Such a relatively simple geometry code is limited in acquiring the accuracy of FAC prediction. Recently, EPRI revisited the geometry code with the intention of updating it. In this study, numerical simulations were performed for two adjacent 90° elbows and the results were analysed in terms of the proximity effect between the two adjacent elbows.

Keywords : *flow accelerated corrosion, computation fluid dynamics, proximity, mass transfer coefficient*

1. Introduction

Flow Accelerated Corrosion (FAC) is a degradation mechanism which attacks carbon and low-alloy steel piping in power plants. FAC is a complex mechanism which is combined with two coupled processes. The first process produces ferrous ions from the interface between oxide film and solution. The second is the transfer of the ferrous ions into the bulk solution across the diffusion boundary layer. For single phase flow, damaged surfaces are usually found to look like “horseshoe pits”. For two phase flow, “tiger striped” appearance is often observed[1)].

Several accidents have been reported around the world since the Surry Unit 2 event in 1986 at which severe elbow failure happened at the downstream of elbow causing four fatalities. At Prairie Power Plant in 1995, downstream of T-bend was failed due to FAC and caused two fatalities. Failure also occurred in Mihama Unit 3 in 2004 at the downstream of orifice and caused five fatalities. The pipe failure accident at Iatan fossil power plant in 2007 resulted in two fatalities. Aside from these tragic events, a considerable number of FAC events have been frequently reported. Having experienced several catastrophic events, utilities have implemented management programs to cope with the severe damages in carbon steel and low-alloy steel piping. Despite of the employment of the utmost efforts, FAC-induced damages have not ceased in the power stations around the world.

To secure the plant safety from damages caused by FAC, some computer codes were developed: CHECWORKS developed by EPRI; CICERO developed by Électricité de France (EDF); COMSY developed by AREVA. These programs can help utilities predict FAC wear rates and properly respond to FAC problems. These programs are useful for estimating FAC wear trend in the plants, although they must be replenished with various input data such as chemistry compositions, flow operating conditions, pipe geometries, etc. Therefore, the estimated prediction results may be seen as vague when the input data are not clearly defined. A prediction program CHECWORKS uses geometry code for calculating the geometry effects. Such a relatively simple geometry code is limited in acquiring the accuracy of FAC prediction. Recently, EPRI tries to update the geometry factor because it was developed in the 1990s and the factor needed to be re-evaluated to reflect the current situations. Table 1 describes geometric factors found in the Reference 1.

According to earlier studies on FAC mechanism, main parameters are material composition (i.e., Cr contents), environmental effects (i.e., chemistry, pH) and hydro-

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Table 1. Geometric enhancement factor for piping component with single phase flow in various models[1)]

Fitting	Geometric factors for FAC				
	Keller	Chexal-Horowits	Remy	Woolsey	Kastner
Straight Pipe	1	1	1	1	1
90° Elbow	5.75 to 13	3.7	2.1	1.7	6.0 to 11
Reducer (large end)		2.5	3.2		
Reducer (small end)		1.8			
Pipe entry	4			2.5[2]	3.58 to 6.24
Expander (large end)		3	3.6		
Expander (small end)		2.8			
Pipe Extension				2[2]	
Orifice	4.0 to 6.0	5	2.8	3.0 to 4.02	
Tee (run)	3.74	5	5.7	2	
Tee Combination (branch)		5			
Tee (run)	18.75	5	5.7		
Tee Separation (branch)		4			

dynamics of fluid (i.e., turbulent kinetic energy, wall shear stress, mass transfer coefficient). Researches on FAC confirmed that Mass Transfer Coefficient (MTC) is the most contributable flow parameter to FAC. MTC is influenced by geometry, velocity, turbulence and surface roughness[2,3)]. Other researches on FAC state that MTC was used to figure out the most FAC susceptible locations. Also, plant and laboratory (experimental) tests were conducted to find out the co-relation between the local mass transfer conditions and FAC wear rate[2-4)].

According to Chilton and Colburn J-factor analogy, heat, momentum and mass transfer are analogous. Under the turbulent condition, MTC can be calculated based on the analogy. Some researchers used the MTC that is correlated with shear stress distribution to predict FAC wear rate by numerical simulation using the commercially available computational fluid dynamic software.

In this study, the numerical simulation was performed for two adjacent 90° elbows and the results were observed in terms of the proximity effect between elbows. The model was selected in feedwater system based on susceptibility analysis. The MTC distribution was observed as the distance increases between the two elbows, and results were analysed to clarify the correlation of closeness effect in terms of the distance between them. The effect of the flow direction was also studied; upward, downward and sideward direction.

2. Computational model descriptions

Feedwater system containing high pressure, high temperature and high velocity fluid is made of carbon steel material piping. This system is one of the most susceptible lines to FAC in the secondary system. Flowing conditions in feedwater system were considered for building a three-dimensional model having two 90° elbows schematically presented in Fig. 1. Water flow was assumed to arrive from an inlet of diameter 0.25 m (D) at x=0. The first and second 90° elbows were assumed to be located at 3.75 m (15D) and 0.5 m (2D), i.e., downstream of inlet along the x-direction and downstream of the first elbow along the y-direction, respectively. 3.75 m (15D) length of upstream from the inlet and 2.5 m (10D) length of downstream from the outlet of second elbow were considered to avoid the significant changes in the flow at the inlet and outlet sections of the elbows.

The operating conditions for the analysis are presented in Table 2. The flow volume and boundary conditions

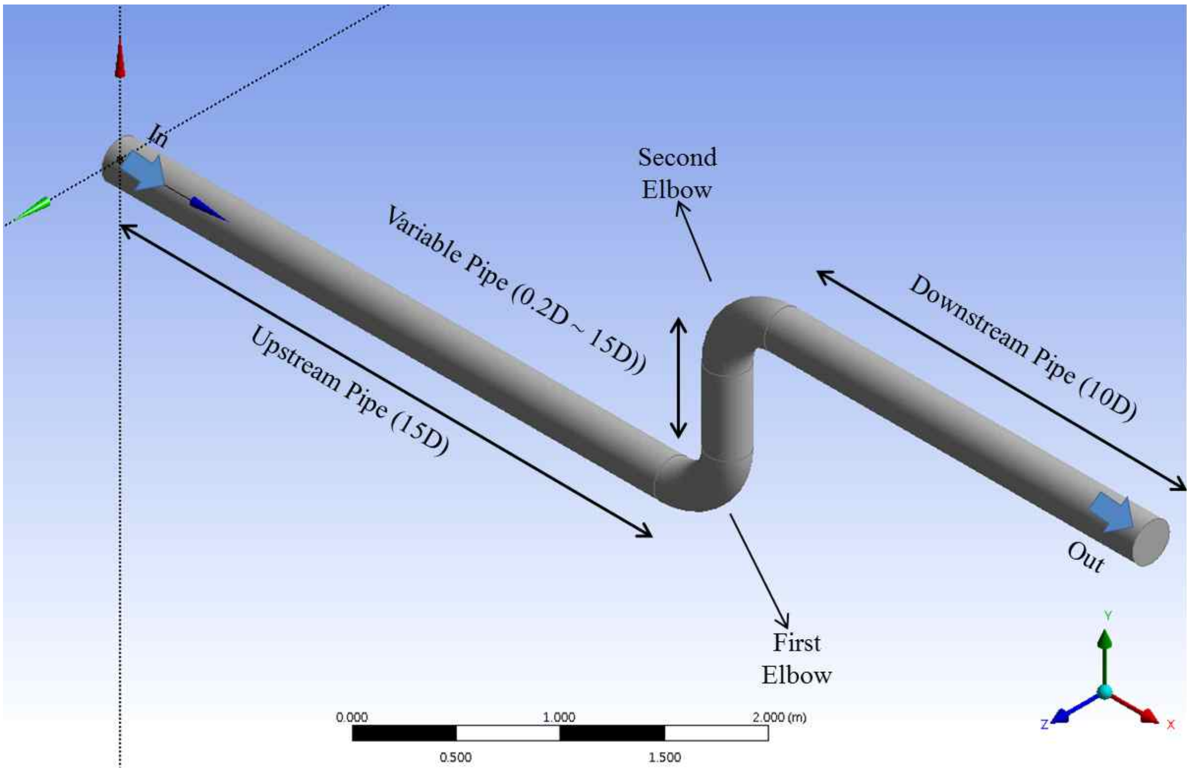

Fig. 1. Computational domain of two adjacent 90° elbows.

Table 2. Operating conditions of the computational model

Parameter	90° elbow	Upstream pipe	Downstream pipe
Diameter (m)	0.25	0.25	0.25
Radius of curvature (m)	0.375	-	-
Length (m)	-	3.75(15D)	2.5(10D)
Fluid	water	water	water
Pressure (bar)	95	95	95
Temperature (K)	508.15	508.15	508.15
Viscosity (kg/m·s)	0.00011506	0.00011506	0.00011506
Density (kg/m^3)	826.69374	826.69374	826.69374
Mean Velocity (m/s)	8.5	8.5	8.5
Sc	12.605	12.605	12.605
Re	1.2368 x 10^7	1.2368 x 10^7	1.2368 x 10^7

were imposed on the ANSYS Fluent R15. In this study, flowing conditions in feedwater system were applied to the two elbows. The uniform inlet velocity of 8.5 m/s was used as the inlet boundary condition.

Reynolds-averaged Navier-Stokes equations (or RANS equations) and turbulence equations for the turbulence kinetic energy (k) and dissipation rate (ε) were employed as a mathematical model for incompressible viscous fluid (water) flowing through the elbows. Turbulence kinetic energy, k, and its rate of dissipation, ε, were obtained from Realizable k-ε model in ANSYS Fluent R15. Standard Wall Function was also used.

To understand the effect of distance between the two elbows, variable pipe distances were used. As the length increases, the computational domain was regenerated and calculation was repeated in the generated domain. The span of the two elbows is 0.2D, 0.4D, 0.8D, 1D, 3D, 5D, 7D, 9D, 11D, 13D and 15D.

Furthermore, to observe the effect of the flow direction to the second elbow, the different flow angle was adopted to the model. The pipes with variable flow from downward and sideward were used to figure out the effect of FAC. Fig. 2 presents the modified models.

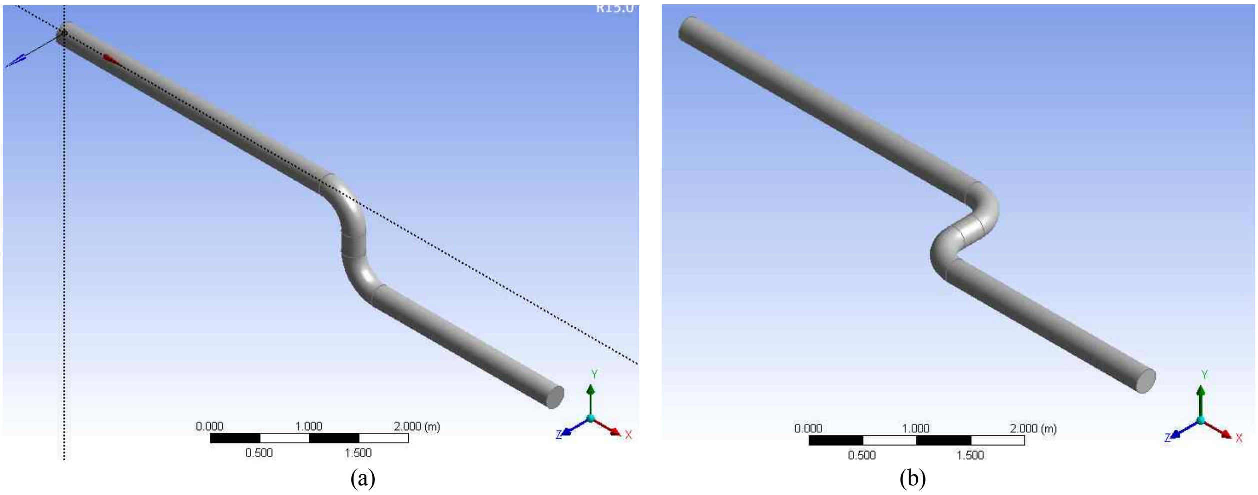

Fig. 2. Modified computational domain (a) downward direction, (b) sideward direction.

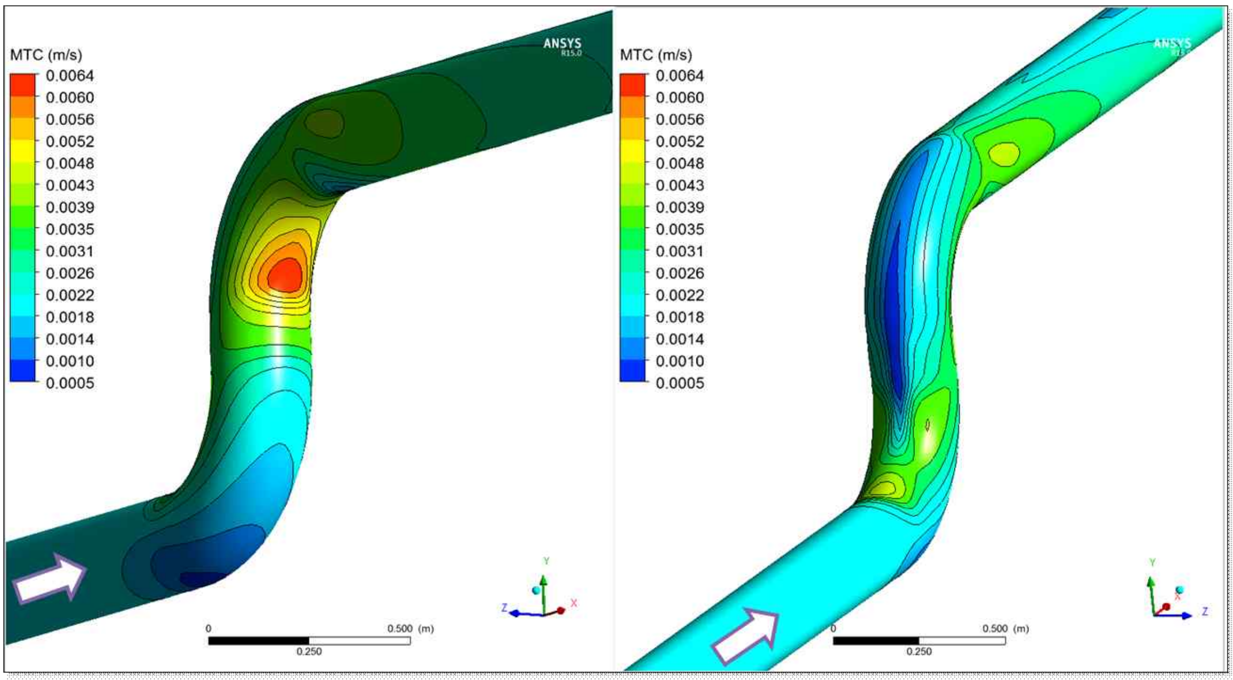

Fig. 3. MTC distribution derived by the Chilton and Colburn analogy in upward direction.

The SIMPLE algorithm was used along with the staggered grid to simultaneously solve the velocity and pressu re equation. The POWER LAW scheme was used. The iterative calculations of primitive variables, such as velocity and kinetic energy, were terminated when the residual criteria reaches 1e^{-3}. The convergence of a solution was checked from the mass flow summary. The flow imbalance was 1.867371e^{-6} kg/s. This is a well converged solution in the sense that the imbalance in two to three orders smaller than that of the inflow/outflow typically indicates good convergence. The mesh was composed of 324,855 nodes. 0.272 transition ratio, 12 maximum layers and 1.2 growth ratio were imposed on the inflation layer.

3. Results and discussion

The distribution of flow parameters and local MTC was analysed under various computational domains to find out the correlation of the proximity effect between the two elbows. MTC distribution was observed in terms of contours to identify the locations that are the most susceptible to FAC under the operating conditions.

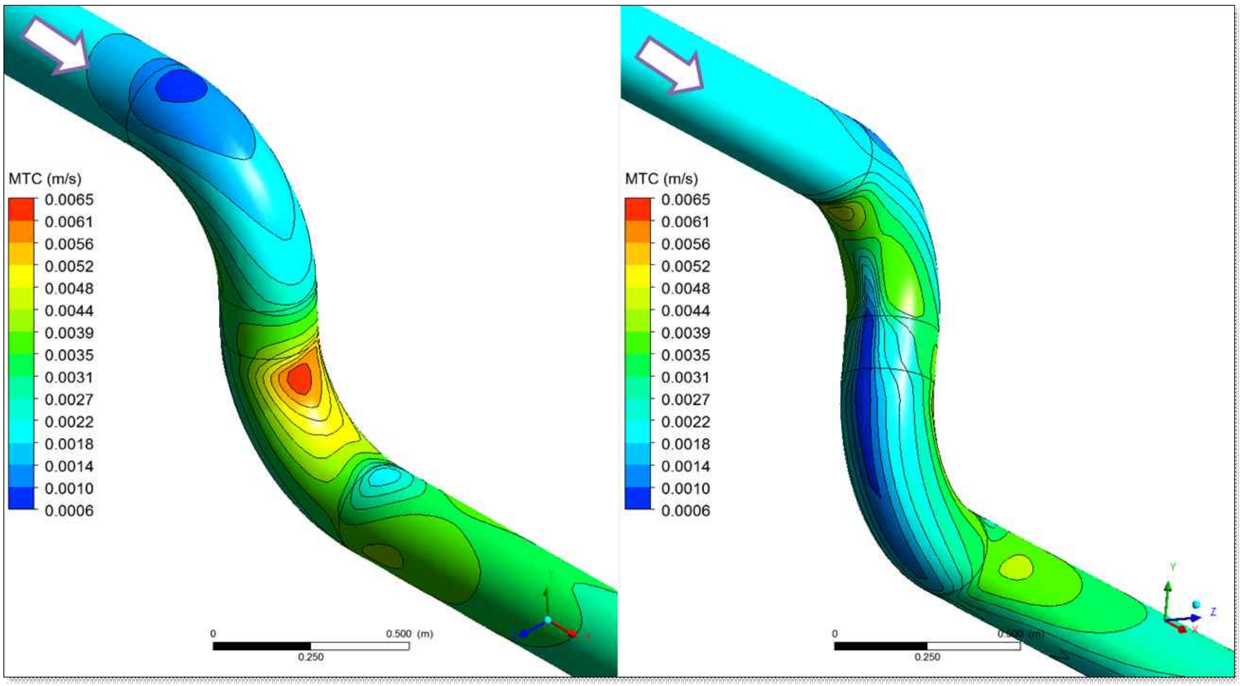

Fig. 4. MTC distribution in downward direction.

FAC is explicable by the mechanism that convective mass transfer of ferrous ions takes place between oxide film and solution through the boundary layer into bulk solution, and this phenomenon is given by Eq. (1);

$$\text{FAC} = \text{K}(C_w - C_b) \tag{1}$$

Where FAC is the mass flux of ferrous ions; K is the mass transfer coefficient (MTC); C_w is the concentration of the ferrous ions at the oxide/solution interface; and C_b is the concentration of the ferrous ions in the bulk fluid. The term of (C_w – C_b) is concentration difference of ferrous ions at the oxide/solution interface and acts a role as a driving force of FAC. In this study, this term is assumed to be constant value. This mechanism is available when mass transfer is dominant factor of FAC rate. The MTC is used to predict FAC wall thinning rate and find out FAC susceptible locations. Based on the Chilton and Colburn analogy, Eq. (2) is given in terms of wall shear stress (τ), mean velocity (U), density (ρ) and Schmidt number (Sc). The values of K were calculated based on the simulation results of wall shear stress[4].

$$\text{K} = \left(\frac{\tau}{\text{U}\rho}\right) * Sc^{-2/3} \tag{2}$$

Fig. 3 presents the results of MTC distribution for the first elbow and the second elbow (i.e., upward direction). From the previous studies[4-6], the results of Chilton and Colburn analogy are in good agreement with the measured wall thickness. FAC susceptible locations in the corresponding components can be found from the MTC distribution results. It is clear in Fig. 3 that the maximum MTC occurs at the intrados. The effect of the flow with downward, and sideward direction was also investigated to figure out FAC susceptible locations. Fig. 4 shows the MTC distribution of downward direction, while Fig. 5 presents the MTC distribution of sideward direction. The results are similar to the upward direction.

The downstream elbow experienced a little higher wear rate induced by FAC than the upstream elbow. To investigate the close proximity effect, the length of variable pipe between two elbows was used. As the length was increased from 0.05 m (0.2D) to 3.75 m (15D), the result was taken using Eq. (3);

$$\text{CPE} = \frac{MTC_S - MTC_F}{MTC_F} \text{ x } 100\ \% \tag{3}$$

Where CPE denotes the close proximity effect; and MTC_S denotes the maximum MTC at the downstream elbow; and MTC_F is the maximum MTC at the upstream elbow[7]. The results are shown in Fig. 6. It was observed

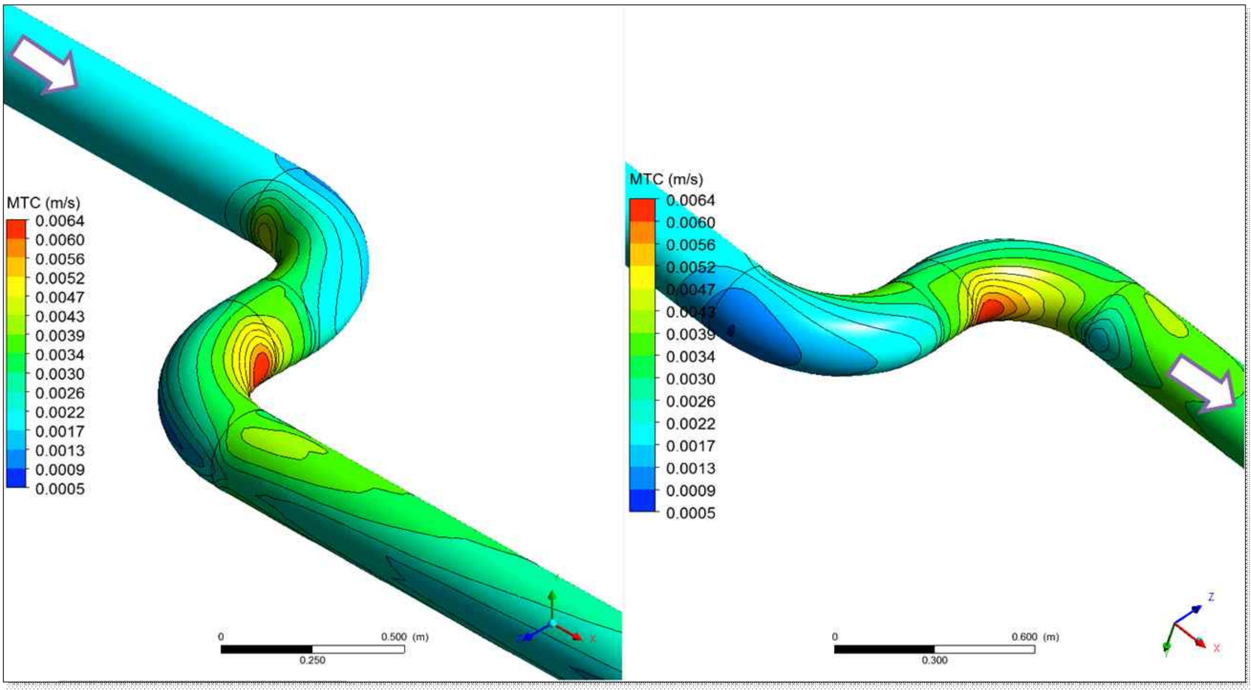

Fig. 5. MTC distribution in sideward direction.

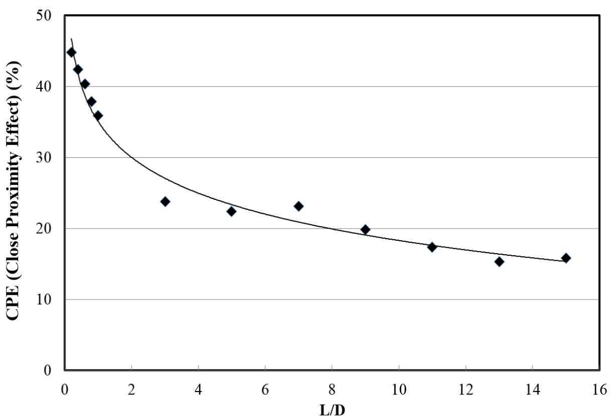

Fig. 6. Effect of L/D on Close proximity effect in term of L/D increase.

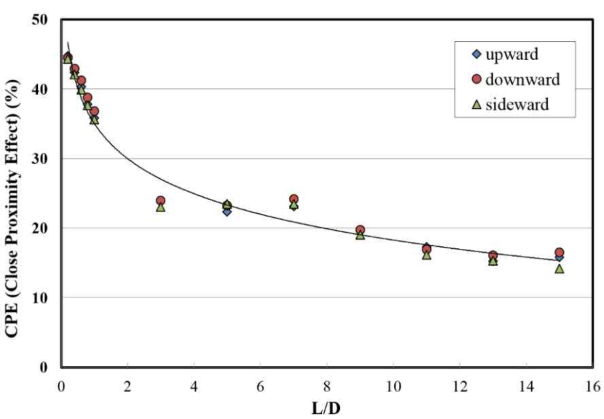

Fig. 7. Effect of L/D on Close proximity effect in 3 different Cases.

that as the distance between two elbows (L/D) increases, the CPE decreases. This is because, as the distance of L/D increases, the second elbow experiences less impact due to the first elbow.

Fig. 7 shows the CPE for the 3 cases of pipe arrangement. It can be explained as same as the result of the previous case. Because the results in 3 cases seem to be little difference and show similar trends, flow direction has little influence on the CPE value.

4. Conclusions

Computational study was performed to figure out the MTC under FAC operative conditions in feedwater system. MTC distribution was investigated to find the most FAC susceptible locations. MTC value was calculated using Chilton and Colburn analogy and wall shear stress value from the CFD results. From the previous studies, Chilton and Colburn equation is in good agreement with the measured data, so that the calculated MTC was used to find FAC susceptible locations.

From the computational simulation results, the most susceptible locations for FAC were observed in terms of the MTC distribution. The maximum MTC value was found at the intrados of elbows, and it is in good agreement with the previous studies.

To find out the effect of the distance between the two elbows, the close proximity effect was observed. Based on the findings of the study, it was confirmed that as the distance increases between the two elbows (L/D), the CPE decreases. The effect of the flow direction change was also investigated with the modified model; downward direction, sideward direction. The results are very close to the results of upward direction model. Because the results in 3 cases seem to be little difference and show similar trends, flow direction has little influence on the CPE value.

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