EFFECT OF NON-FULLY DEVELOPED FLOW AND THE SURFACE ROUGHNESS IN AN ELBOW PIPE UNDER THE INDIAN NPP FLOW CONDITIONS

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ABSTRACT

Flow accelerated corrosion (FAC) is a wall-thinning degradation mechanism that involves the three steps such as metal oxidation, diffusion, and convection. As a part of the computational study, diffusive mass transfer and convective mass transfer analysis can be carried out. This paper intent is to examine convective mass transfer in feeder pipes under diverse settings of nuclear power plants (NPP) piping. The flow and mass transfer of operating fluid i.e., demineralised water in the double elbow was simulated under the conditions of the Indian NPP feeder water system. The analysis carried out in this study is based on the position of the first elbow. The upstream region of the first elbow is not fully developed flow is considered as the piping system in NPP contains such type of construction of piping. For this analysis, the upstream horizontal limb of the double elbow is considered to be of different lengths ranging from 30mm to 150mm. The most influential parameter to predict the highly vulnerable FAC locations is the mass transfer coefficient (MTC). To analyse the MTC, the Chilton - Colburn analogy used which is in terms of wall shear stress. These simulated results will help to find the locations that are vulnerable to FAC and these resultant locations are useful for developing the targeted inspection plans.

1. INTRODUCTION

FAC is a degradation mechanism and is usually encountered in carbon steel piping at certain operating conditions in nuclear power plants. Primary and secondary circuits of NPPs are susceptible to this phenomenon. The primary side of the pressurized heavy water reactors (PHWR) also gets affected other than the primary side of the piping (Singh et al., 2012; Roychowdhury et al., 2012).

Consequently, the present study deals with the nature of the flow under FAC conditions in critical geometry namely double elbow for various lengths of the upstream horizontal limb. H.P.Rani et.al. (2014) has carried out a detailed study about the FAC in the double elbow pipe uncer Indian NPP conditions. The close proximity effect analysis has been carried out in the double elbow by H.P.Rani et.al.(2014), Pietralik and Schefski(2011). From this study is it analysed that the impact of first elbow on second elbow. For this analysis, various lengths of limb in between the first and second elbow has been considered and it is observed that the fully developed flow reduces the effect of first elbow on second elbow. In this sequence the present study carried out by considering different length of upstream horizontal limb. The flow development at the upstream of the first elbow has been studied in detail. The lengths are considered to be ranging from 30mm to 150mm.

2. MATHEMATICAL FORMULATION

Under the feeder pipe environment, demineralised water flow inside a three-dimensional pipe containing the two right-angled (90o) bends schematically presented in the Fig. 1 is considered. Demineralised water flow arrives from a circular inlet channel of diameter 0.059m (D) at various values of x such as x = -0.09m, -0.11m, -0.13m, and -0.15m.

The governing equations for an incompressible viscous fluid i.e., demineralised water passing through an elbow is continuity equation along with the Reynolds averaged Navier-Stokes equations (RANS), for calculating the turbulent quantities the kinetic energy (k) and dissipation rate (ε) equations, for calculating thermal quantities the energy equation and for calculating the concentration of the species the species transport equation. From the transport equations of Realizable k-ε model the turbulent kinetic energy, k and its rate of dissipation ε were obtained ANSYS Fluent® (2023).

3. COMPUTATIONAL PROCEDURE

The solution of the governing equations corresponding to the operating the conditions FAC of Indian NPP was calculated by using the ANSYS Fluent® (2009). In the first phase of analysis, the computational domain of the flow model was created using ANSYS Design Modeller.

The grid generated in the computational domain is uniform and clustered near the bends. This mesh is generated based on the non-dimensional wall distance y^+, which is given by $\sqrt{\frac{\tau_w}{\rho}}.\frac{y}{\nu}$, where τ_w denotes the wall shear stress. The distance between the wall and the first calculating node is chosen to be small, so as to have, y^+ < 300 ANSYS Fluent® (2009) based on the following calculations,

$$\text{First cell height} = \text{RF}\left[\frac{y^+ D^{0.125}}{0.199}\left(\frac{\mu}{U_1\rho}\right)^{0.875}\right]\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

here to create a fine mesh refinement factor considered to be 1.
The operating conditions of the Indian NPP feeder water system were considered in the double elbow. At the inlet uniform velocity of 3m/s has given. On the wall, constant temperature, constant concentration, and no-slip conditions are imposed. At the outlet, for pressure, the zero-gradient is considered. The FAC operating conditions of Indian and CANDU NPP are considered from the previous study of H.P.Rani et.al. (2014).
To solve the velocity and pressure equations simultaneously the SIMPLE algorithm with the staggered grid was used. Convection and diffusion transports are discretized on a uniform grid using the POWER LAW scheme. The primitive variables, such as velocity, kinetic energy, rate of dissipation, thermal and species variables iterative calculations terminated when the residual criteria reached 1e-7 in all the investigations.

4. RESULTS AND DISCUSSION

The computational analysis has been carried out for the small length of the piping component therefore the mass transfer analysis can better predicts the locations which are exposed to FAC (H.P.Rani et al., 2014; Pietralik and Smith, 2006; Pietralik, 2008; Pietralik and Schefski, 2011; Fingjun et al., 2008). The convective mass transfer is the last step of the FAC mechanism. In this process, from the oxide water interface the species (ferrous ions) convectively transfer to the bulk water. It was analyzed by

$$Ffe = K\ (Cw - Cb) \ldots\ldots\ldots\ldots\ldots\ldots..\ (2)$$

where Ffe is the mass flux of species (ferrous ions), K is the MTC, Cw is the concentration of the ferrous ions at the oxide water interface and Cb is the concentration of the ferrous ions in the bulk fluid. From the equation (2), for the calculation of FAC rate the wall concentration and bulk concentration required for only long length piping component but for the short length piping component FAC rate can be calculated in terms of MTC(K). In the present study the MTC analysis has been carried under the operating conditions of Indian NPP. Under the plant operating conditions, the flow is considered to be turbulent flow. For the turbulent flow K is calculated using the Chilton–Colburn equation (Fingjun et al., 2008) wall shear stress (τ), mean velocity (U), density (ρ) and Schmidt number (Sc) as follows.

$$K= (\tau / U\ \rho)\ Sc\text{-}2/3 \ldots\ldots\ldots\ldots\ldots\ldots..\ (3)$$

To examine the relation between mass transfer coefficient and FAC rate, a comparison between the experimental wall thickness data of an Indian power plant and computationally calculated MTC from the equation (3) on 90^{o} bend shown in the figure (2) (H.P.Rani et.al.,[2014]). The locations which are susceptible to FAC are observed to be in the same place.
Velocity is the one of the major hydrodynamic parameters which affects the FAC [H.P.Rani et.al. (2014), Pietralik and Schefski (2011)]. In the considered computational domain the distribution of velocity is analysed for various lengths of the upstream horizontal limb and the remaining lengths of the piping components are considered to be the same. The lengths of the upstream limbs are considered to be L/D<1, L/D=1, and L/D>1 as shown in the Fig. 3. It is observed that for the non-fully developed flow in the upstream horizontal limb, the flow velocity is high in the vertical limb, whereas for the fully developed flow velocity is observed to be less in the vertical limb.

Turbulent kinetic energy is also another important hydrodynamic parameter of FAC, helps to predict the locations which are susceptible to FAC [H.P.Rani et.al.(2014), Pietralik and Schefski(2011).]. The maximum turbulent kinetic energy at both elbows for various lengths of the upstream horizontal limb is observed to be as in Fig.4. From the figure it is observed that turbulent kinetic energy is more for L/D>1 than for L/D<1. It is also observed that the turbulent kinetic energy is more at the first elbow when L/D<1 due to the non-fully developed floe at the upstream of the first elbow, where as it is more at the second elbow when L/D>1 due to the fully developed flow at the first elbow and due to carrying of disturbances created at the first elbow [H.P.Rani et.al.(2014), Pietralik and Schefski(2011)].
From the previous study, we have analysed that the effect of the first elbow on the second elbow due to the flow development between first and second elbow i.e., the close proximity effect [H.P.Rani et.al.,]. To study the effect of the non-fully developed flow on FAC in the double elbow, the first elbow was considered at the different distances ranging from 30mm to 150mm from the inlet. As MTC distribution resembling the FAC behaviour, the MTC distribution has been captured at the first and second elbow for various lengths of the first limb of the double elbow. Here it is observed that the maximum MTC is almost same at the first and second elbows when L/D<1 and

for L/D>1, but when L/D≅1 MTC is more at the first elbow than at the second elbow due to transition of flow from non-fully developed flow to the fully developed flow.

5. CONCLUSIONS

The effects of the non-fully developed flow on FAC have been studied in terms of velocity, turbulent kinetic energy, and MTC in the double elbow. For this study, the first limb is considered to be of different lengths ranging from 30mm to 150mm. The velocity distribution exhibits that the velocity is more for L/D<1 with the non-fully developed flow at the upstream of the first elbow. The kinetic energy distribution demonstrates that the maximum value of TKE appears to be more at the first elbow for L/D<1 and it is more at the second elbow for L/D>1. The MTC distribution is showing that the fully developed flow at the upstream region of both elbows has less effect on the elbows. These results help to predict the locations which are susceptible to FAC.

ACKNOWLEDGEMENTS

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FIGURES

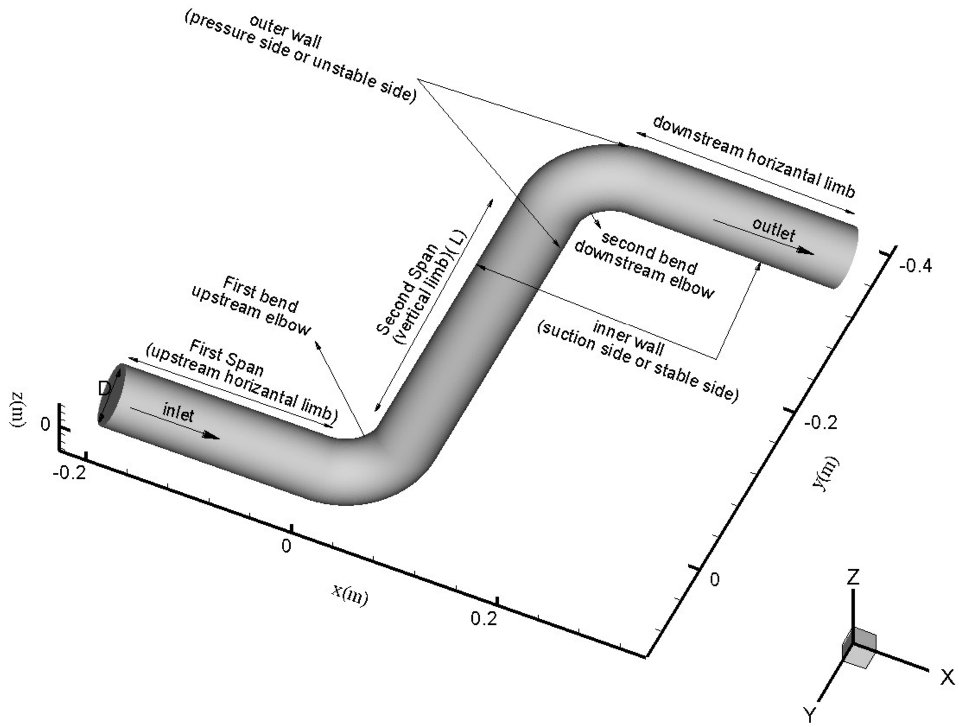

Fig. 1. Computational Domain

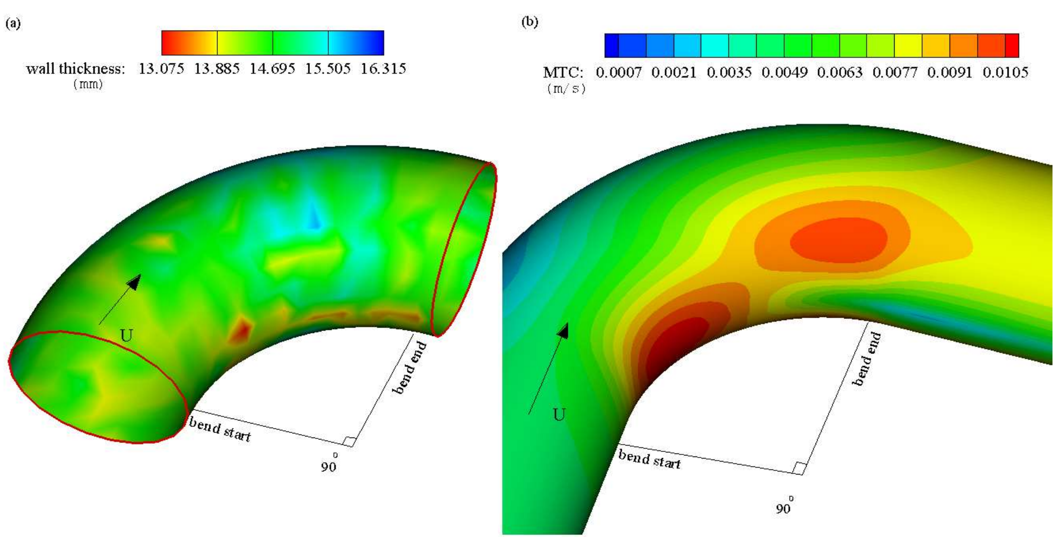

Fig. 2. Comparison of contours of (i) Experimental data of measured wall thickness data and (ii) computationally calculated MTC.

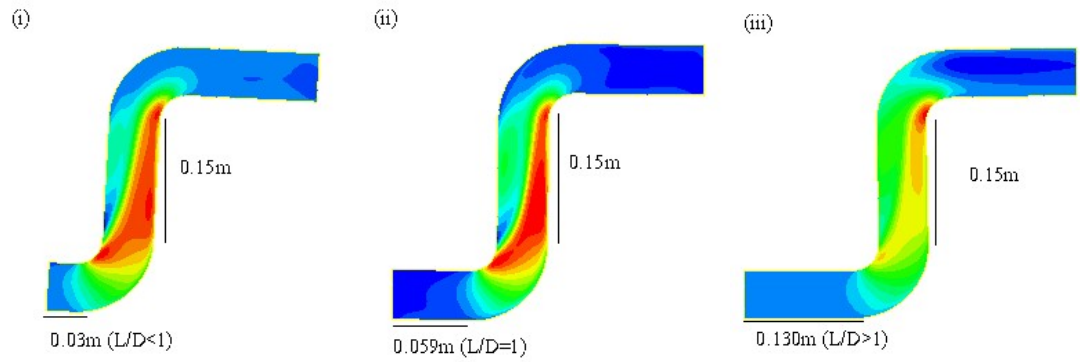

Fig. 3. Transverse velocity distribution in the computational domain for different lengths [(i) 0.03m (ii) 0.059m and (iii) 0.130m] of upstream horizontal limb.

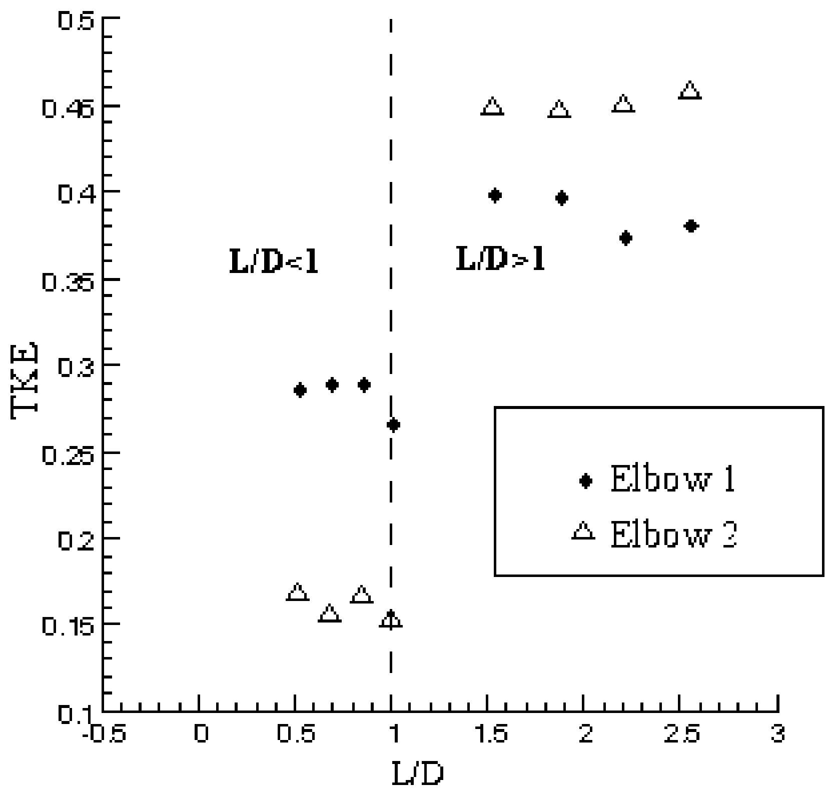

Fig. 4. Maximum turbulent kinetic energy at both upstream elbow and downstream elbow for the various lengths of the upstream horizontal limb ranging from 30mm to 150mm.

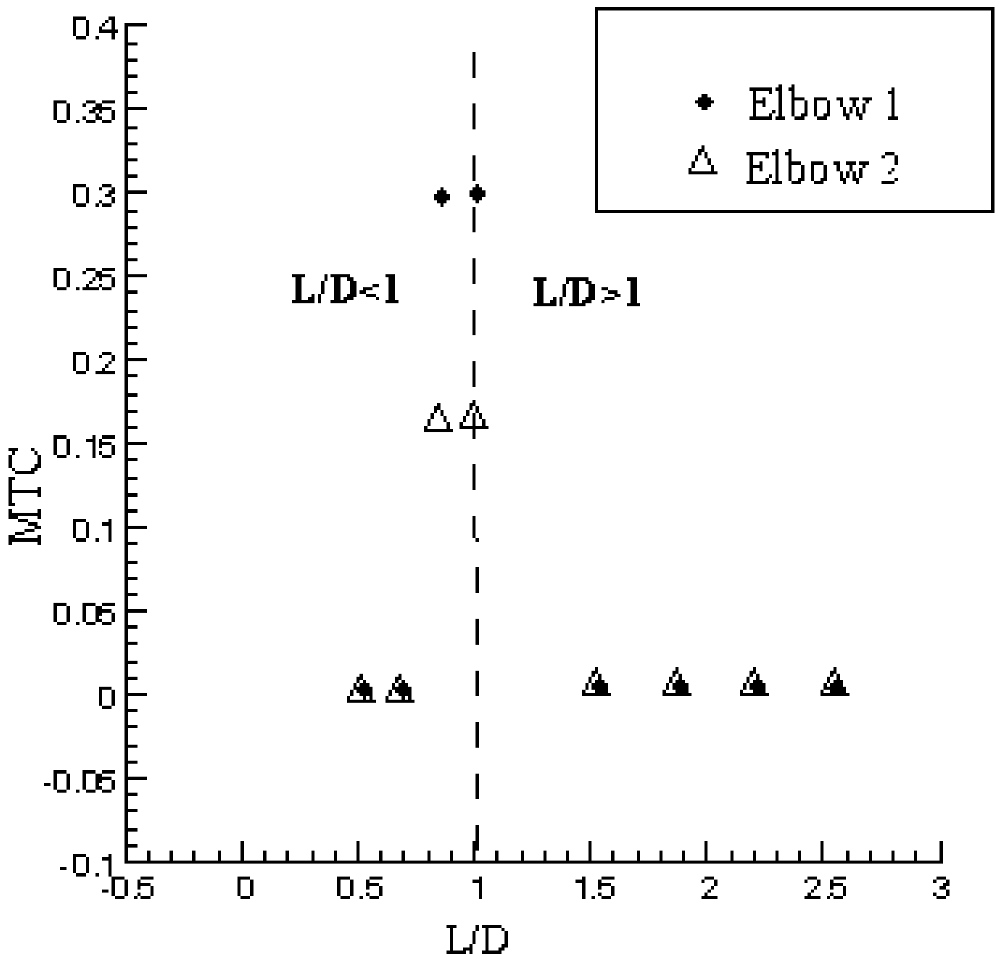

Fig. 5. Maximum mass transfer coefficient at both upstream elbow and downstream elbow for the various lengths of the upstream horizontal limb ranging from 30mm to 150mm.