Correlation between Flow Accelerated Corrosion and Wall Shear Stress Downstream from an Orifice

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Abstract
Flow accelerated corrosion (FAC) thinning rate downstream from an orifice was measured under different velocity conditions in a high-temperature water test loop to understand the effects of flow velocity on FAC thinning rate. The FAC tendency differed downstream and upstream from the orifice. The metal loss increased linearly with time downstream from the orifice, though metal loss rate gradually decreased with time upstream. FAC rate increased as flow velocity increased, particularly from 1D to 3D. The maximum FAC thinning rate increased in proportional to the 0.51th power of the mean cross-sectional velocity in this experiment. The root mean square (RMS) of wall shear stress predicted by large eddy simulation (LES) had a clear relationship with FAC thinning rate. This result indicated that FAC thinning rate can be described as a function of the wall shear stress. Additionally, the mass transfer coefficient estimated from the RMS of wall shear stress had an almost linear correlation with FAC thinning rate.

Key words: Flow Accelerated Corrosion, Pipe Wall Thinning, Pipe Flow, Orifice, Wall Shear Stress, Mass Transfer Coefficient

1. Introduction
Flow accelerated corrosion (FAC) is an important issue for aging fossil and nuclear power plants. FAC causes thinning of pipe walls which occasionally leads to a piping rupture accident. FAC occurs near the pipe geometry where flow is strongly disturbed such as downstream from an orifice. The Japan Society of Mechanical Engineers published rules on pipe wall thinning management in 2005(1). FAC was treated in the rules and since then they have been used to evaluate remaining lifetime from thinning rates of pipe wall thicknesses based on such non-destructive inspection techniques of the wall thicknesses as the ultrasonic technique. Predicting the distribution of FAC thinning rates is, therefore, useful for planning non-destructive inspections.

For prediction of FAC thinning rates, understanding of factors influencing FAC is important. Generally, influencing factors are temperature, pH, dissolved oxygen, material composition and fluid dynamics factor(2). FAC studies from the viewpoint of fluid dynamics factor have mainly been focused on mean cross-sectional velocity(3)(4), but recently the
The relation between FAC and local flow field has been reported\(^5\)–\(^7\). It is said that the essential fluid dynamics factor influencing FAC is the mass transfer coefficient near a pipe wall, and most studies have been conducted based on this concept.

The authors also have studied the influence of local flow field on FAC downstream from an orifice experimentally and numerically\(^8\). The goal of the present study was to develop a numerical method with which the effect of local flow field on FAC can be evaluated. To this end, the FAC thinning rate downstream from an orifice was measured using a high-temperature water test loop. In addition, the orifice flow field was simulated numerically and compared with the measured velocity profiles obtained by laser Doppler velocimetry (LDV) to investigate the predictive performance. The evaluation parameter employed in the study was the wall shear stress (WSS) based on the analogy between momentum and mass transfer on the wall surface. The WSS represents the momentum flux near the wall and the authors thought that it had an analogy with the diffusion flux of iron ions\(^9\). According to the results, the profile of the root mean square (RMS) of WSS predicted by large eddy simulation (LES) was relatively similar in shape to that of the profile of experimental FAC thinning rate data.

In the previous paper\(^8\), the velocity was constant in the FAC experiment and the relation between FAC thinning rate and velocity was not investigated. Hence, in this study, FAC thinning rate of an orifice flow was measured under different velocity conditions to understand the effects of velocity on FAC thinning rate. In addition, FAC thinning rates were compared with simulated wall shear stress and estimated mass transfer coefficient to investigate the relationship between them.

### Nomenclature

| Symbol | Description | Unit |
|--------|-------------|------|
| \(C_f\) | Skin friction coefficient | [-] |
| \(D\) | Pipe diameter | [m] |
| \(D_{Fe}\) | Mass diffusion coefficient of iron ions | [m\(^2\)/s] |
| \(k_e\) | Mass transfer coefficient | [m/s] |
| \(Re\) | Reynolds number, \(Re = \frac{U_{ave}D}{\nu}\) | [-] |
| \(Sc\) | Schmidt number | [-] |
| \(U_{ave}\) | Mean cross-sectional velocity | [m/s] |
| \(x\) | Longitudinal direction | [m] |

### Greek letters

| Symbol | Description | Unit |
|--------|-------------|------|
| \(\nu\) | Kinematic viscosity | [m\(^2\)/s] |
| \(\rho\) | Density | [kg/m\(^3\)] |
| \(\tau_w\) | Instantaneous wall shear stress | [N/m\(^2\)] |

### Subscript

| Symbol | Description |
|--------|-------------|
| RMS | Root mean square |

### 2. Experimental methods

#### 2.1 Experimental facilities

The test loop is shown in Fig. 1, and it consisted of a hot water tank and its loop, an automatic pressure control system using nitrogen gas, a feed water system with degasification unit, a water chemistry control system, and a measurement system for water chemistry parameters. The detailed explanation of the experimental facilities was reported previously\(^8\).

During the experiment, pressure of the hot water tank, temperature and flow rate in the
loop were measured. In the measurement system for water chemistry parameters, dissolved oxygen, conductivity and pH were measured at low pressure and room temperature. In addition, loop water was sampled directly from the test loop taking care not to expose the sampled water to air, and pH and iron concentration were measured using handy-type measuring instruments.

![Image of test loop](image_url)

**Table 1** FAC experimental conditions (the values in parenthesis are minimum and maximum values during the experiment)

|                  | Run 1          | Run 2          |
|------------------|---------------|---------------|
| Experimental period [h] | 117 | 60 | 93 | 57 |
| Mean cross-sectional velocity $U_{av}$ [m/s] | 1.4 | 5 | 2.1 | 3.5 |
| $Re$ (150°C, 1.5 MPa) | $3.6 \times 10^5$ | $1.2 \times 10^6$ | $5.3 \times 10^5$ | $8.9 \times 10^5$ |
| Temperature [°C] | 149.8 |       |
| Pressure [MPa] | 1.5 |       |
| Dissolved oxygen [ppb] | 0.1 (0 to 0.2) | 0.1 (0 to 0.4) |
| pH at room temperature | 6.0 (5.8 to 6.2) | 6.0 (6.0 to 6.3) |
| Conductivity [$\mu$S/cm] | 0.28 to 0.78 | 0.78 to 1.28 | 0.45 to 1.19 | 1.19 to 1.45 |
| Iron concentration [ppm] | 0.03 to 0.12 | 0.12 to 0.20 | 0.12 to 0.19 | 0.19 to 0.21 |

### 2.2 Experimental conditions

The test section and corrosion sensors for FAC thinning rate measurement are shown in Fig. 2. The stainless steel (SUS 304) pipe had a 50 mm inner diameter and the orifice diameter was 24.3 mm. Corrosion sensors made of carbon steel plate (STPT 42: Ni, 0.02 wt. %; Cr, 0.04 wt. %; Mo, 0.01 wt. %) were insulated from the SUS 304 pipe with a resin covering and implanted in the pipe wall so that one surface of the plates was exposed to the fluid (hot water) flowing in the pipe as shown in Fig. 3. Four sensors were installed in the circumferential direction at $1D$ and $2D$ downstream from the orifice, two were at $3D$ to $5D$ downstream, and four were at $3D$ upstream. The FAC thinning rate was measured by the electric resistance method. The detailed explanation was reported previously. The experimental conditions are shown in Table 1. Two experimental runs, Run 1 and Run 2, were conducted to clarify the effect of flow velocity on FAC thinning rate. Mean cross-sectional velocity was changed from 1.4 to 5 m/s during Run 1 and from 2.1 to 3.5
m/s during Run 2. The case of $U_{ave} = 1.4$ m/s was previously reported\(^{(8)}\). Water temperature was controlled around 150 °C and water was pressurized to 1.5 MPa to avoid cavitation downstream from the orifice. Dissolved oxygen was almost always under 0.1 ppb. Conductivity and iron concentration increased gradually during the experimental period.

3. Results and discussion

3.1 Time history of metal loss

Figure 4 shows time histories of metal loss of corrosion sensors at $2D$, $3D$ and $5D$ downstream and $3D$ upstream from the orifice as obtained in Run 1. At $2D$ to $5D$ downstream (Fig. 4 (a), (b)), the metal loss increased linearly with time. In Run 1, when mean cross-sectional velocity $U_{ave}$ was changed from 1.4 m/s to 5.0 m/s at 117 h, the gradient of the metal loss curve increased sharply. On the other hand, metal loss rate at $3D$ upstream (Fig. 4 (c)) gradually slowed with time. In addition, the influence of flow velocity change was small and the gradual decrease of the metal loss rate continued. A possible reason for the different tendency upstream and downstream was the difference of the mass transfer coefficient near the wall. According to the experimental results by Bignold et al.\(^{(9)}\), metal loss rate of carbon steel was linear with time. However, in the case of 1% Cr content steel, metal loss rate was initially rapid and quickly decreased to a low metal loss rate during the initial formation of the oxide film from an essentially oxide-free surface. In Bignold et al.'s case, the Cr content seemed to affect the growth rate of the oxide film. A similar situation might occur upstream from the orifice in this study, namely, the low mass transfer coefficient near the wall led to the growth of oxide film and the decrease of metal loss rate. This meant that a gradual decrease of metal loss rate might occur even if the corrosion sensors are located downstream, when the mass transfer coefficient is low due to low flow velocity.
3.2 Effect of flow velocity on FAC thinning rate

Figure 5 shows the distribution of the FAC thinning rate downstream from the orifice. The origin of the longitudinal direction $x$ was at the outlet cross section of the orifice. The plotted FAC thinning rates were the circumferentially averaged values. The qualitative tendency of the distribution was the same for different flow velocities; the maximum FAC rate appeared at $1D$ or $2D$, and gradually decreased downstream at $3D$ and $4D$. FAC rate increased as flow velocity increased, particularly from $1D$ to $3D$. 

![Graph showing metal loss over time at different downstream positions and flow velocities.](image-url)
The relationship between the maximum FAC thinning rate and Reynolds number \((Re = \frac{U_{ave}D}{\nu})\) is shown in Fig. 6. The maximum FAC thinning rate increased with \(Re\). It is known that FAC thinning rate increases with increasing flow velocity. However, the relationship between the FAC thinning rate and flow velocity depends on experimental facilities. One experimental study showed a linear correlation\(^{10}\) between FAC thinning rate and flow velocity, while another study reported that the FAC thinning rate increased with the square of flow velocity\(^3\). One possible reason has been given that the FAC thinning rate is influenced by turbulence near the wall as well as flow velocity and turbulence depends on the scale of the experimental facilities\(^{11}\). Hence, there is no uniform dependency between FAC thinning rate and flow velocity and it is preferable to investigate the influence of flow field using a parameter near the wall. In the following sections, the influence was investigated using the wall shear stress as the evaluation parameter near the wall.

![Fig. 5 Distribution of FAC thinning rate downstream from the orifice for each flow velocity (The error bars indicate the circumferential variation of FAC rate and the measurement uncertainty due to the variation of reference plate thicknesses, 5%).](image1)

![Fig. 6 Dependence of maximum FAC thinning rate on Reynolds number downstream from the orifice](image2)
3.3 Correlation between FAC thinning rate and predicted wall shear stress

To understand the relationship between FAC thinning rate and the RMS wall shear stress, LES simulation results from the previous paper\(^8\) were used. It should be noted that the simulation conditions were: \(U_{ave} = 0.453 \text{ m/s}, \text{ room temperature and atmospheric pressure; these differed from the experimental conditions. Hence, the distribution of } \tau_{w,RMS} \text{ values predicted by LES } (U_{ave} = 0.453 \text{ m/s}, \rho = 997 \text{ kg/m\(^3\)}) \text{ was converted once to the distribution of the skin friction coefficients } C_f \text{ using Eq. (1), and the wall shear stresses of the FAC experimental conditions were obtained from Eq. (1) again using the obtained distribution of } C_f \text{ and experimental conditions (different flow velocities } U_{ave} = 1.4, 2.1, 3.5 \text{ and } 5.0 \text{ m/s, } \rho = 918 \text{ kg/m\(^3\) under } 150 \text{ °C and } 1.5 \text{ MPa).}

\[
C_f = \frac{\tau_{w,RMS}}{\frac{1}{2} \rho U_{ave}^2}
\]  

Here, \(\rho\) is density and \(U_{ave}\) is mean cross-sectional velocity. It must be noted that \(C_f\) downstream from the orifice was assumed to be independent of density and flow velocity and to be constant. As described before\(^8\), the flow structure downstream from the orifice did not depend on the flow velocity in the range of \(Re = 2.3 \times 10^4 \text{ to } 1.2 \times 10^5\), and this assumption would be reasonable.

Figure 7 shows the relationship between FAC thinning rate and the RMS wall shear stress \(\tau_{w,RMS}\) derived by the above method. As shown in the figure, there is a clear relationship between FAC thinning rate and the RMS wall shear stress \(\tau_{w,RMS}\). The fitting curve was obtained by the least square method as the following.

\[
FAC \text{ rate} = 0.23 \tau_{w,RMS}^{0.40}
\]

Here, units of FAC rate are mm/year and of \(\tau_{w,RMS}\), Pa. In this way, FAC thinning rate was described as a function of the wall shear stress.

![Fig. 7 Relationship between FAC rate and wall shear stress downstream from the orifice](image-url)
3.4 Estimated mass transfer coefficient and FAC thinning rate

As described in Sec. 1, the mass transfer coefficient near the pipe wall is the essential fluid dynamics factor influencing FAC. Mass transfer coefficient $k_e$ can be estimated from the wall shear stress based on the analogy between momentum and mass transfer as:

$$k_e = \frac{\tau_w}{\rho U_{ave} Sc^{-2/3}}$$

(3)

where $Sc$ is Schmidt number ($Sc = \nu / D_{Fe}$). $\nu$ is kinematic viscosity and it was set to the value at $150 \, ^\circ C$, 1.5 MPa, $\nu = 1.99 \times 10^{-7}$ m$^2$/s. $D_{Fe}$ is mass diffusion coefficient of iron ions and it was set to the value at pH = 7 and $150 \, ^\circ C$, $D_{Fe} = 2.21 \times 10^{-8}$ m$^2$/s with reference to Yoneda et al. (12). Hence, $Sc$ was about 9. Figure 8 shows the distribution of mass transfer coefficient downstream from the orifice calculated from Eq. (3) using $\tau_{w,RMS}$. Since the cases of experimental conditions ($U_{ave} = 2.1-5.0$ m/s) were not simulated as described in Sec. 4.3, values in Fig. 8 were derived from the simulation result of $U_{ave} = 0.453$ m/s using Eqs. (1) and (3). The derived mass transfer coefficients were compared with FAC thinning rates in Fig. 9. Their relationship is almost linear and this trend corresponds to previously reported results (5)(10)(13). However, for the present findings, the linear relationship for $k_e < 2.5 \times 10^{-3}$ m/s seems to be different from that for $k_e > 3.0 \times 10^{-3}$ m/s. FAC thinning rate does not increase so much with mass transfer coefficient for $k_e > 3.0 \times 10^{-3}$ m/s; their relationship in a wider $k_e$ region is still unclear at this stage and a more detailed study and more FAC experimental data are needed. It should be noted that the dependency of the mass transfer coefficient on FAC thinning rate was said to vary at different temperatures and pH values (11). For example, another experimental study (3) reported that FAC rate was proportional to the third power of mass transfer coefficient. In any case, Fig. 9 indicates that the mass transfer coefficient estimated from $\tau_{w,RMS}$ can be used to evaluate FAC thinning rate.

Fig. 8  Predicted mass transfer coefficient downstream from the orifice
4. Conclusion

FAC thinning rate downstream from an orifice was measured under different velocity conditions to understand the effects of flow velocity on FAC thinning rate. In addition, FAC thinning rates were compared with the simulated RMS of wall shear stress and estimated mass transfer coefficient. The following conclusions were obtained.

(1) The FAC tendency upstream from the orifice was different from that downstream. The downstream metal loss increased linearly with time although upstream metal loss rate gradually decreased with time. The different tendencies were attributed to the difference of the mass transfer coefficient near the wall which affected the growth of oxide film.

(2) The qualitative tendency of the distribution of FAC thinning rate was the same for different flow velocities. FAC rate increased as flow velocity increased, particularly from 1D to 3D.

(3) There was a clear relationship between FAC rate and the predicted RMS of wall shear stress by LES. The FAC thinning rate would be described as a function of the wall shear stress.

(4) The mass transfer coefficient estimated from the RMS of wall shear stress had an almost linear correlation with FAC thinning rate.

References

(1) Japan Society of Mechanical Engineers, Codes for Power Generation Facilities – Rules on Pipe Wall Thinning Management –, JSME S CA1-2005, 2005 (in Japanese).

(2) Dooley, R. B. and Chexal, V. K., Flow-Accelerated Corrosion of Pressure Vessels in Fossil Plants, International Journal of Pressure Vessels and Piping, Vol. 77, No. 2-3, (2000), pp. 85-90.

(3) Bignold, G. J., Garbett, K., Garnsey, R. and Woolsey, I. S., Erosion-Corrosion in Nuclear
Steam Generators, *Water Chemistry of Nuclear Reactor Systems* 2, British Nuclear Engineering Society (1981), pp. 5-18.

(4) Heitmann, H. G. and Schub, P., Initial Experience Gained with a High pH Value in the Secondary System of PWRs, *Water Chemistry of Nuclear Reactor Systems* 3, Vol. 1, British Nuclear Engineering Society (1983), pp. 243-252.

(5) Yoneda, K., Ohira, T., Tanji, K., Akiba, S., Niiyama, K., Morita, R. and Inada, F., Evaluation of Hydraulic Factors Affecting Flow Accelerated Corrosion and Its Verification with Power Plant Data, *Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference* (PVP2009), No. PVP2009-77486, (2009-7).

(6) Kojo, R., Kuroda, Y., Kondo, M. and Tsuji, Y., Flow Accelerated Corrosion and Mass Transfer Rate in Orifice Downstream Flow, *Proceedings of the 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics* (NURETH-14), Paper No.NURETH14-542 (2011-9).

(7) Fujisawa, N., Yamagata, T., Kanno, S., Ito, A. and Takano, T., The Mechanism of Asymmetric Pipe-Wall Thinning behind an Orifice by Combined Effect of Swirling Flow and Orifice Bias, *Nuclear Engineering and Design*, Vol. 252, (2012), pp. 19-26.

(8) Utanohara, Y., Nagaya, Y., Nakamura A. and Murase, M., Influence of Local Flow Field on Flow Accelerated Corrosion Downstream from an Orifice, *JSME Journal of Power and Energy Systems*, Vol. 6, No. 1 (2012), pp. 18-33.

(9) Bignold, G. J., De Whalley, C. H., Garbett, K., and Woolsey, I. S., Mechanistic Aspects of Erosion-Corrosion under Boiler Feedwater Conditions, *Water Chemistry of Nuclear Reactor Systems* 3, Vol. 1, British Nuclear Engineering Society (1983), pp. 219-226.

(10) Yoneda, K., Morita, R. and Inada, F., Quantitative Evaluation of Effective Factors on Flow Accelerated Corrosion (Part 2) - Modeling of Mass Transfer Coefficient with Hydraulic Features at Wall -, *CRIEPI Report*, L07015, Central Research Institute of Electric Power Industry, (2008), (in Japanese).

(11) Japan Society of Mechanical Engineers, *Technical Report, Research Committee on Application of New Findings and Technology to Improve Pipe-Wall-Thinning Management*, P-SCCII-3, (2012), (in Japanese).

(12) Yoneda, K., Morita, R. and Fujiwara, K., Quantitative Evaluation of Effective Factors on Flow Accelerated Corrosion (Part 4) - Evaluation of Wall Thinning Profile in Piping Elements -, *CRIEPI Report*, L09006, Central Research Institute of Electric Power Industry, (2010), (in Japanese).

(13) Ducruex, J., The Influence of Flow Velocity on the Corrosion-Erosion of Carbon Steel in Pressurized Water, *Water Chemistry of Nuclear Reactor Systems* 3, Vol. 1, British Nuclear Energy Society (1983), pp. 227-233.