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FLOW ACCELERATED CORROSION AND MASSTRANSFER RATE IN ORIFICE DOWNSTREAM FLOW

K. Retsu[1], K.YujiB[1],M. Kondo[1] and Y.Tsuji[1]

[1] Department of Energy Engineering and Science, Nagoya University,
Chikusa-ku, Nagoya 464-8603, Japan

Abstract

Flow Accelerated Corrosion (FAC) is one of the issues to be noticed considerably in plant piping management. For the integrity and safety of the plant, the wall-thinning and thinning rate due to FAC should be clearly predicted in pipe wall inspection. In this paper, we study FAC from the view point of flow dynamics. The mass transfer coefficient is measured by the electrochemical method behind the orifice. Changing the orifice size, the peak location of mass transfer coefficient and its maximum value is evaluated by the flow condition and orifice parameter.

1. Introduction

Flow Accelerated Corrosion (FAC) relates not only to flow dynamics but also material science. It is very complicated phenomena. Although FAC is the similar to general erosion-corrosion, the effect of fluid flow is added to that of corrosion, which consists of two main processes. One is to form soluble ferrous ions at the oxide film or solution interface, and then those ions diffuse into solution. The other process, which is sought to control the FAC rate, is the diffusion of ferrous ions through the boundary layer. Close to the wall the viscous sub-layer (laminar boundary layer) is generated and the turbulent flow exists in outer region. The former is the problem of materials and the latter concerns the fluid mechanics. When the Reynolds number increases, the viscous sub-layer thickness decreases, and the diffusion rate of ferrous ion increases. These two processes are even further enhanced under turbulent and separated flow conditions. Because the turbulence eddy penetrates into viscous layer and increases the associated shear stress. In order to understand the FAC from the view point of hydrodynamics, it is necessary to have detailed information about the diffusion process. The ferrous ions diffuse into solution, where the diffusion process is characterized by the mass transfer coefficient, but the diffusion is strongly affected by the flow conditions.

Here, we try to quantify as far as possible the effect of mass transfer behind an orifice. A well documented approach, based on the limiting current condition for the diffusion of reacting species, has been widely used by previous researchers such as Sydberger and Lotz [1], Runchal

[2] , Rizk et al. [3], Miyashita et al., [4].This technique is employed in conjunction with a well-designed flow apparatus. A ferri-ferrocyanide redox electrode and with small diameter gold electrodes located at different circumferential positions in the cell wall behind an orifice.

The present study is motivated by the accident in second cooling system in Mihama power plant in 2002 (Yoneda [5]). It is aimed at investigating the mass transfer rates as a basis for an accurate assessment of FAC. The ratio between the orifice diameter and pipe diameter is defined as β. This parameter is varied as 0.62, 0.7 and 0.8. The location of maximum mass transfer rate expressed as a function of β. Also the relation of its maximum value to the Reynolds number is discussed. These are useful information for understanding the FAC mechanism and industrial piping management.

2. Experimental Conditions

A schematic diagram of the apparatus used is shown in Fig.1. A centrifugal pump maintains a supply of liquid from the reservoir. Electro fluid of ambient temperature is pumped from the water tank into the pipe and it is circulated in a closed pipe. After the flow is developed enough, it passed over the test section. At the test section, there are point-electrodes, which are made of gold and have 1mm diameter, and 13 electrodes are set up in the direction of the flow (see Fig.2). The voltage is applied to the electrode, and the oxidation-reduction reaction of electro fluid is caused on the surface of electrodes.

The pipe is made of vinyl chloride of 44 mm in the diameter. A test section is located after the flow developed at $90D$ from the corner section. There is an orifice inside the test section, which can be clearly seen in Fig. 2 (the enlarged picture of the test section), in which d and D represent the diameter of the orifice and pipe, respectively. Actually the ratio of d d to D, namely $\beta (= d/D)$, is employed in this paper to describe the size of orifice. β is varied as 0.62, 0.7 and 0.8. The Reynolds number ($\mathrm{Re} = U_c D/\nu$, where U_c is cross sectional velocity and ν is kinematic viscosity) is set to 25000, 35000, 45000, and 55000.

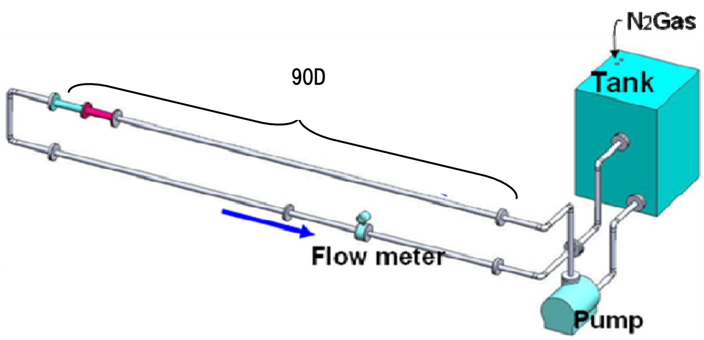

Fig.1 Schematic view of test loop.

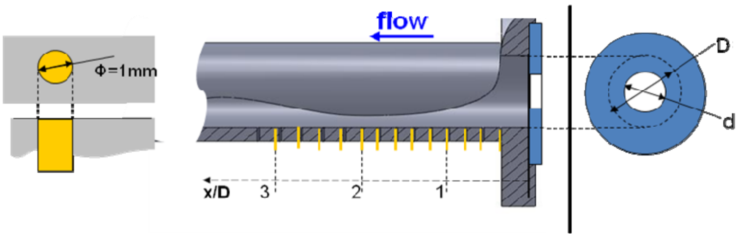

Fig.2 Test section behind the orifice. The orifice size is defined by the parameter $\beta\,(=d/D)$

We use the electrochemical method for the measurement of the mass transfer. The voltage is applied to the electrode, and the oxidation-reduction reaction of electro fluid is caused on the surface of electrodes. When this reaction takes place, the current runs to the electrode. This reaction rate is determined by the diffusion rate of the flow.

This current (limiting current) shows the mass transfer from the wall surface. Therefore, the limiting current enable us to evaluate the mass transmission rate of iron ion directly. The reaction employed is that between the ferricynide and ferrocynide ions:

[Cathode] $Fe(CN)_6^{3-} + e^{-1} \rightarrow Fe(CN)_6^{4-}$

[Anode] $Fe(CN)_6^{4-} \rightarrow Fe(CN)_6^{4-} + e^{-1}$

The mass transfer coefficient k is derived by the relation : $\mathrm{i}/(\mathrm{An_eF}) = \mathrm{k}(\mathrm{c_b} - \mathrm{c_i})$, where A is surface area of electrode, n_e is valence charge of an ion, F is Faraday constant, c_b is a concentration at the bulk, c_i is a concentration near the surface, and i is limiting current (Mizushina, [6]). The main advantage of electrochemical mass transfer measurement is that the qualitative results are obtained. As the limiting current density corresponds to the instantaneous mass transfer rate, fluctuation in the mass transport can be studied in addition to the time-averaged mass transfer.

3. References and Discussions

Figure 3 shows the mass transfer coefficient measured in the downstream of orifice at $\beta = 0.5$. Mass transfer rate shows its maximum value at some distance and gradually decreases. We define the maximum value of mass transfer rate and its location as $k_{\max}$ and $x_{\max}$,respectively. In order to evaluate $k_{\max}$ and $x_{\max}$, the following empirical function is suggested here.

$$k = a(x/D)^b \exp\{-c(x/D)^d + e\} \;, \tag{1}$$

where a, b, c, d and e are fitting parameters. The solid lines show the fitted lines for each Reynolds number. We find that the Eq.(1) can approximate well the experimental results. If the fitting function is extended in far down-stream, the mass transfer rate approaches zero by $x/D \approx 15$. Therefore, this results show a possibility that FAC may appear in wide area behind the orifice. The maximum mass transfer rate k_{max} depends on Reynolds number, but the location x_{max} is less dependent on.

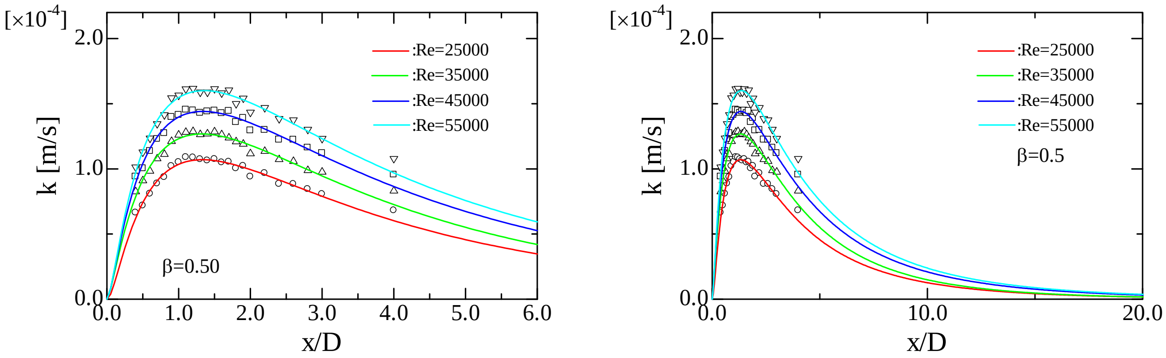

Figure 3 Mass transfer rate profile for $\beta = 0.5$. x is the distance from the orifice. solid lines are fitting by Eq. (1).

Figure 4 shows the maximum mass transfer rate normalized by k_0. Here k_0 is the mass transfer rate measured in the straight pipe at the same Reynolds number. The normalized value indicates the similar profiles, but the Reynolds number dependence is not zero exactly, or the ratio decreases gradually as Reynolds number increases. The ratio varies significantly depending on the orifice parameters (see Fig.4 (b)). For small β, k/k_0 indicates the larger values and its maximum location, x_{max}, goes in the down stream. We are measuring the velocity field by PIV at the same experimental conditions [7]. From the PIV measurement, the reattachment point is clarified, and it is indicated by arrows in the figure. The maximum mass transfer occurs behind the orifice but it locates upstream of reattachment point.

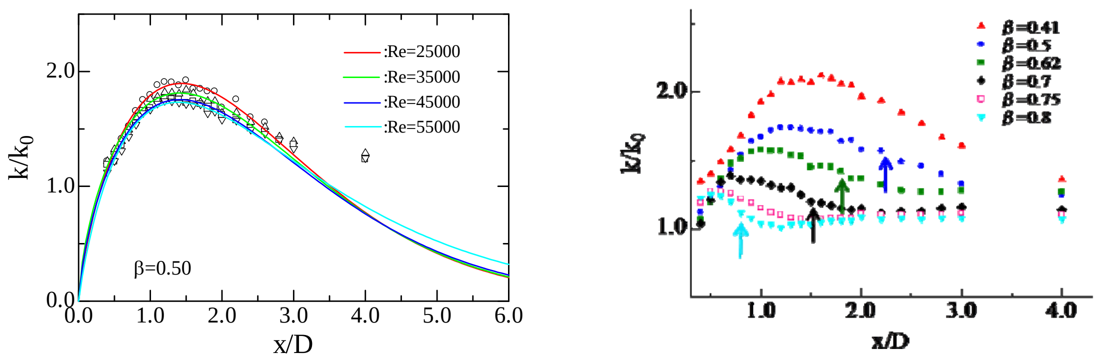

Figure 4 Mass transfer rate normalized by that of straight pipe. Solid lines are fitting by Eq.(1).

The Maximum value of the ratio $(k/k_0)_{\max}$ is usually called a shape factor. It is convenient to evaluate roughly the amount of transfer enhancement depending on the shape of flow field, such as orifice, elbow, T-junction. The shape factor of 0.16 is suggested for the orifice flow [8]. In the present study, we find that the shape factor is not constant but it is a strong function of orifice parameter $\beta\,(=d/D)$ as plotted in Fig. 5.

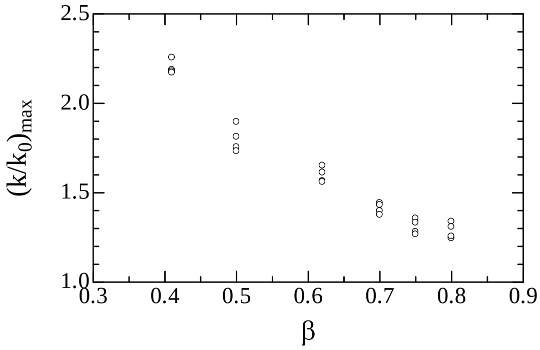

Figure 5 Maximum value of normalized mass transfer rate against orifice parameter $\beta\,(=d/D)$.

The main objective of this study is to find out the flow parameters which affect on the mass transfer coefficient. The detailed flow field information is necessary for this purpose, and now it is under going by PIV measurement [7]. In the present study, we focus on the maximum mass transfer rate $k_{\max}$ and try to find out its relation with mean velocity field. The flow parameter is introduce as

$$U_D = (D/d)^2 U_0\,, \tag{2}$$

which indicates the mean velocity averaged in a cross section of the orifice. The data obtained in different Reynolds number ($\mathrm{Re} = 25000, 35000, 45000, 55000$), orifice ratios ($\beta = 0.41$, 0.5, 0.62, 0.7, 0.75, 0.8) and Schmidt number ($Sc = 1170, 2770$) are plotted in Fig.6(a). The relation between $k_{\max}$ and U_D is approximated by a simple power-law form,

$$k_{\max} = A(Sc) \times U_D^{\;0.47}\,, \tag{3}$$

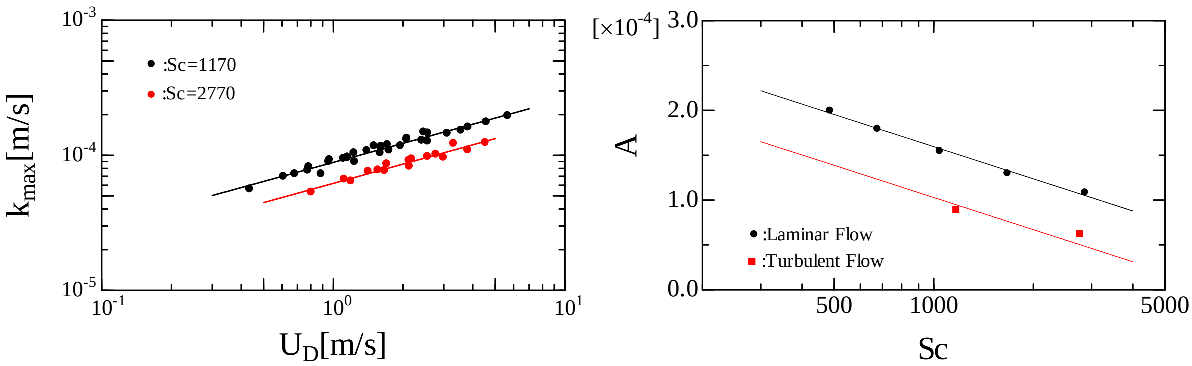

Figure 6 (a) relation between $k_{\max}$ and U_D. (b) relation between A and Sc.

where constant A is estimated to be a function of Schmidt number. The maximum mass transfer rate is simply predicted by the velocity U_D. This results does not show that the mass transfer is affected by U_D directly, but the flow field close the wall is determined by the mean velocity U_D. Further researches are still necessary to reveal the relation between $k_{\max}$ and U_D.

Using the small apparatus, we changed the Schmidt number, and studied the functional form of A. In the small apparatus, the flow is not turbulent but laminar. We suppose that the dependence of A on Schmidt number in laminar flow is the same with that in turbulent flow, and suggest the following relation (plotted in Fig.6(b)).

$$A = \{-5.17 \ln(S_c) + 46.0\} \times 10^{-5} \tag{4}$$

Coupling Eq.(3) and Eq.(4), we can estimate the maximum mass transfer rate by U_D. On the location of $x_{\max}$, it is found experimentally that $x/h \cong 5$, where h is the orifice height defined as $h = (D-d)/2$. This relation is physically understood by PIV measurement [7]. Velocity field close to the wall shows the self-similar profile when they are normalized by U_D and h. The detail will be reported in the near future.

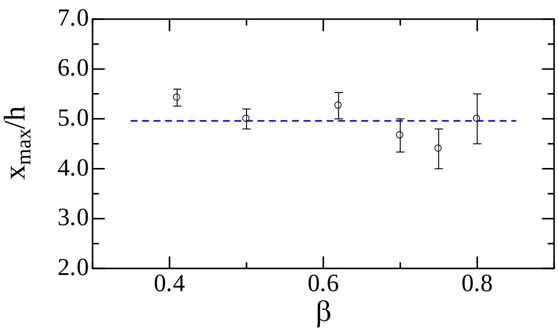

Figure 7 Maximum mass transfer rate location normalized by orifice height.

4. Conclusions

Using the techniques based on the limiting current condition for the diffusion of reacting species, the mass transfer coefficient behind the orifice is measured. The obtained results may be summarized as follows.

(1) The maximum mass transfer rate $k_{\max}$ has a strong relation with U_D. The relations of Eq.(3) and Eq.(4) are found by analyzing all the date in the present experiments. From these relations, the maximum mass transfer rate can be estimated by U_D.

(2) Mass transfer rate has its maximum value $k_{\max}$ at some distance from the orifice. The location $x_{\max}/h$ is almost independent of Reynolds number nor orifice parameter β. The maximum location is estimated as $x_{\max}/h \cong 5$, it is located upstream of reattachment point.

(3) The shape factor, defined as $(k/k_0)_{\max}$, is not constant. But depends on the orifice parameter β. It varies from 2.3 to 1.3 as β increases from 0.41 to 0.8.

5. References

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