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Effect of Large Scale Motions on the Shear Stress Fluctuations Behind an Orifice in a Straight pipe

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ABSTRACT

Many piping rupture accidents are caused by flow accelerated corrosion (FAC) in nuclear energy power plants. For safety operation, it is important to reveal mechanism of wall thinning phenomena due to FAC.

In this paper, we study the relation of the vortex structures with wall shear stress fluctuations. We visualize the flow field behind the orifice by the stereo particle image velocimetry (PIV), and the shear stress fluctuations are also measured by the electrochemical method simultaneously. Changing the width of measurement cross section from the orifice, we investigated the vortex organizations near the electrode and found that they are related with shear stress fluctuations.

INTRODUCTION

In nuclear power plant, the flow accelerated corrosion (FAC) is one of the important topics of interest associated with wall thinning phenomena for safety operation. There are a lot of piping rupture accidents caused by FAC. The mechanism of FAC has the common opinion of being based on the dissolution of the oxidization film formed in the surface of metal, and diffusion of the iron ion by fluid flow. FAC is easy to occur in the region generated turbulence of flow, for instance behind the orifice, pipe tee, and the bent. In these regions, there is a high probability occurring piping rupture accident because the wall thinning rate is not uniform in the circumference of the pipe. From the view point of hydrodynamics, one of the most important factors of FAC is the shear stress.

Over the surface of pipe, there are a lot of small vortex structures and the coherent structures caused by velocity fluctuation. Furthermore, at downstream from the orifice, it is clear that strong vortex structures are caused by the separation from orifice edge flow in near the wall. For this reason we assume that the vortex behavier plays an important role for the mechanism of wall thinning phenomena. In the present study, the purpose is considering the relation of the vortex structures and shear stress fluctuation. When we visualize the flow field behind the orifice by stereo particle image velocimetry (PIV), the shear stress fluctuation is also measured by the electrochemical method at the same time. We define the vortex region by calculating the second invariant of velocity gradient tensor (Q-criterion) and compare the time fluctuation of Q-criterion with the shear stress.

EXPERIMENTAL CONDITIONS

Stereo PIV measurement is a kind of fluid visualization methods. The flow is seeded with small particles. The particles in the flow are illuminated in sheet twice with a small time separation and the reflected light of the particles is recorded by two cameras. From these images, velocity field is calculated by displacement of the particles. In this method, it is possible to measure three velocity components in a measurement plane. A schematic diagram of the experimental device is shown in Fig.1. The experimental loop is composed of a test section made of acrylic, two high-speed cameras, scheimpflug adapters, and a double-pulse laser. The acrylic section consist of a pipe of 46mm diameter, orifice ($\beta = 0.62$), water jacket and prism for suppressing refraction. Here, we defined the orifice size β as a ratio of d to D, where d and D represent the diameter of the orifice and pipe, respectively. We use double-pulse YLF laser which emits with the wavelength of 527nm and energy of 10mJ/pulse. Through an optical arrangement, the laser beam is transformed into sheet shape whose thickness is 1mm. We irradiate the spanwise component, length from orifice is 0.1D, and 0.9D. A sampling frequency is fixed as 1 kHz. Reynolds number is set to 25000 ($\mathrm{Re} = U_c D/\nu$, where U_c is cross sectional velocity and ν is kinematic viscosity).

Simultaneously, the shear stress fluctuations are measured by the electrochemical method (T. Mizushina 1971). Point-electrodes made from gold (1mm diameter) are set up on the flow direction at the pipe wall (see Fig.1). The electrolytic solution is circulated through the loop. The voltage was applied to the electrode, and the oxidation-reduction reaction of electro fluid is caused on the surface of electrodes. At this time, the current running electrode is measured as electric signal. This signal shows the mass transfer from the surface. Therefore, the mass transfer rate of iron ion is evaluated directly by the limiting current. The limiting current is:

$$i = An_e FN \tag{1}$$

where A is surface area of electrode, n_e is valence charge of an ion, F is Faraday constant. Mass flux N from the surface to flow follows Fick's law:

$$N = k(C_w - C_b) \tag{2}$$

where C_b and C_w are concentration in the bulk and at the surface, respectively. k is the mass transfer coefficient. From equations (1) and (2), the mass transfer coefficient is derived as the following relation:

$$k = \frac{i}{An_e F\left(C_w - C_b\right)} \tag{3}$$

From the discussions in Mizushina (1971), the mass transfer rate has a relation with shear stress fluctuations as $\tau \propto k^{1/3}$. Therefore, we can estimate directly the shear stress fluctuation by way of measuring the limiting current.

Q criterion is one of the methods to extract the vortical motions. Q is defined as the second invariant of the local velocity gradient tensor W_{ij}. This criterion is derived as:

$$Q = \frac{1}{2} W_{ij} W_{ji} = \frac{1}{2}\left(\Omega_{ij}\Omega_{ji} - S_{ij}S_{ji}\right) \tag{4}$$

where Ω_{ij} is the vorticity tensor and S_{ij} is the rate-of-strain tensor. Q is a difference between Ω_{ij} and S_{ij}. Hence, the vortex region corresponds to the positive values of Q. A non-zero Q threshold is employed to clearly identify the vortical region separating them from the measurement noise.

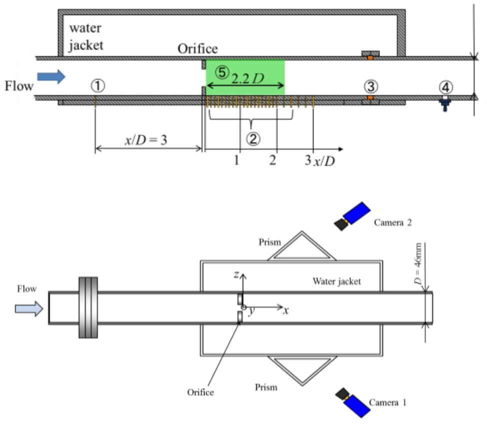

Fig.1(a) Sketch of the test section (front view): ① upstream electrode (cathode); ② downstream electrodes (cathode); ③ counter electrode (anode); ④ reference electrode; ⑤PIV measurement area .Fig.1(b) Sketch of stereo-PIV (top view): to present a clearer view of the laser sheet, only the first and the last downstream electrodes are shown

RESULTS AND DISCUSSIONS

Time-series of flow field data by Stereo PIV measurement are consist of three velocity components in two dimensional domain. Visualizing the vortex organizations by Q-criterion needs three velocity components in three dimensional field. Based on Taylor's hypothesis, we replace time axis with spatial axis and compute streamwise velocity gradient, then Q-criterion behind an orifice is applied. In this process, the flow attenuation is ignored because difference of streamwise length is infinitesimal. It is expected that vortex organizations in the range of some extent near the electrode shear stress fluctuations. Figure 2 shows the time fluctuation of mass transfer coefficient (equivalent to shear stress fluctuations) and Q at $x = 0.1D$ and $x = 0.9D$ from the orifice, respectively. There is a close relation between two quantities because the large mass transfer coefficient locates at a Q peak period. The Q criterion is roughly closer to the fluctuation cycle of mass transfer coefficient. At a location $x = 0.1D$, the fluctuation period is longer than that of $0.9D$ and mass transfer coefficient is higher than that of $0.9D$. These are because vortex structures affect the fluctuation of shear stress.

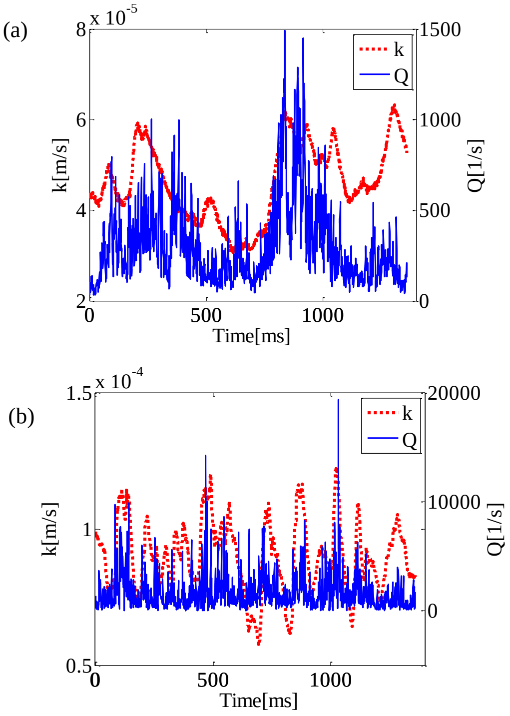

Fig. 2 the time fluctuation of mass transfer coefficient and Q criterion at (a) $x = 0.1D$ and (b) $0.9D$ (right) from the orifice.

Figure 3 shows the three-dimensional contour plot of space-time correlation of streamwise velocity and shear stress fluctuations. To make the electrode position easily distinguishable, we use a transparent gray plane (x/R = 2) to represent the streamwise position of the electrode. In this study, the Schmidt number of the solution is very high (1940), and the electrode diameter is 1 mm, which is small compared with the pipe diameter (46 mm). Therefore, the concentration boundary layer is not fully developed and is believed to be well within the viscous sublayer. That is, the mean concentration varied within the viscous sublayer. However, Fig. 2 suggests that the local velocity field relatively far from the wall electrode, for example, has an obvious correlation coefficient with the wall shear stress at x_{max}, even in the shearlayer region. This result reveals that large-scale flow structures in the flow affect the wall shear stress.

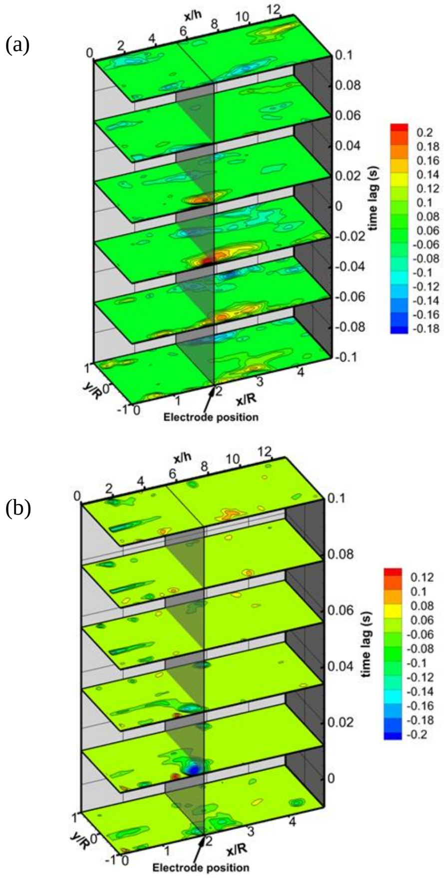

Fig.3 Spatio-temporal correlation coefficient between fluctuations of shear stress at $x = 0.1D$ (R is a radius of pipe) and local velocity fluctuations (a) streamwise, (b) vertical component

[1] T. Mizushina, Advances in Heat Transfer, vol.7, Academic Press, New York, USA , pp.87- 160, (1971)

[2] F. Shan, A. Fujishiro, T. Tsuneyoshi, Y. Tsuji, Int. Journal of Heat and Mass Transfer, 73, 542–550(2014).

[3] F. Shan, A. Fujishiro, T. Tsuneyoshi, Y. Tsuji, Exp Fluids 54, 1553,(2013).