



Mechanism of non-axisymmetric pipe-wall thinning in pipeline with elbow and orifice under influence of swirling flow



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HIGHLIGHTS

- Pipe-wall thinning due to flow accelerated corrosion is studied.
- Pipeline geometry consists of elbow and orifice in swirling flow.
- Velocity field and mass transfer rate are measured in pipeline.
- Non-axisymmetric pipe-wall thinning occurs behind orifice.

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ABSTRACT

In this study, the mechanism of non-axisymmetric pipe-wall thinning that led to a pipeline break in the Mihama nuclear power plant in 2004 is evaluated in a scale-model experiment in a water tunnel having an elbow and orifice under the influence of swirling flow. The velocity fields are measured by stereo particle image velocimetry, and the mass transfer rate is measured by a benzoic acid dissolution method at Reynolds number $Re = 3 \times 10^4$ with and without swirling flow. The non-axisymmetric swirling flow is found to be generated behind the elbow, even when the axisymmetric swirling flow is supplied in the upstream of the elbow. The secondary flow generated in the elbow is not suppressed in the pipeline 10 diameters downstream of elbow in the swirling flow, and in this flow geometry, the non-axisymmetry of the flow is greatly magnified downstream of the orifice. The measured mass transfer rates downstream of the orifice under the influence of swirling flow indicate that the Sherwood number distribution on one side of the pipe is enhanced and that on the other side is reduced owing to the appearance of the non-axisymmetric swirling flow, which results in the occurrence of non-axisymmetric pipe-wall thinning downstream of the orifice.

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1. Introduction

Wall thinning of a pipeline in a nuclear/fossil power plant is an important topic of interest from the viewpoint of the safety management of the power plant. The main cause of pipe-wall thinning is known to be flow-accelerated corrosion (FAC), which refers to the phenomenon of turbulent diffusion of the wall materials of carbon steel into the turbulent bulk-flow through the pipeline surface. Although FAC is affected by the temperature, pH, and oxygen concentration of the fluid flow and the concentration of chromium in the carbon steel, the mechanism of FAC is also governed by fluid

mechanics, such as the influence of the flow field and the turbulence near the thinning wall. The FAC phenomenon is often observed to occur in the wall material in highly turbulent flows, such as the pipe flow downstream of the orifice, elbow, and tee junction of power plants (Keller, 1974; Sanchez-Caldera, 1984; Dooley and Chexal, 2000; Hwang et al., 2009; Pietralik, 2012).

The pipeline break disaster that occurred in the Mihama nuclear power plant in 2004 is considered a typical example of an FAC accident behind the orifice (NISA, 2005). A schematic illustration of the Mihama pipeline is shown in Fig. 1; it consists of an elbow, orifice, tee junction, and straight pipe. The most interesting aspect about the pipeline is that non-axisymmetric pipe-wall thinning occurs downstream of the orifice (diameter ratio of 0.6) in pipeline A (Fig. 1), where the pipe break is found, whereas almost symmetric pipe-wall thinning occurs downstream of the orifice in pipeline B despite the presence of the elbow and orifice in this pipeline. Fig. 1

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Nomenclature

c	concentration [kg/m ³]
c_b	concentration in bulk flow [kg/m ³]
c_w	concentration at wall [kg/m ³]
D	molecular diffusion coefficient [m ² /s ²]
d	pipe diameter [m]
K	mass transfer coefficient [m/s]
k	turbulent energy [m ² /s ²]
R	pipe radius [m]
r	radial distance from pipe center [m]
Re	Reynolds number ($=Ud/\nu$) [-]
S	swirl intensity [-]
Sc	Schmidt number ($=\nu/D$) [-]
Sh	Sherwood number ($=Kd/D$) [-]
U	bulk velocity [m/s]
u, v, w	velocity components in x, y, z direction, respectively [m/s]
v_θ	circumferential mean velocity [m/s]
x, y, z	coordinates [m]
$\delta h/\delta t$	wall thinning rate [m/s]
ν	kinematic viscosity of fluid [m ² /s]
ρ	density of water [kg/m ³]
ρ_b	density of benzoic acid [kg/m ³]

also illustrates the wall-thinning distribution in the cross-section of the pipe one diameter downstream, which indicates the non-axisymmetric pipe-wall thinning in pipeline A. On the other hand, an experiment by NISA (2005) showed the presence of swirling flow in pipeline A but almost no swirl in pipeline B. This result suggests that the non-axisymmetric pipe-wall thinning can be related to some extent to the swirling flow; however, the correlation between them is unclear owing to the complexity of the flow field in the pipelines. In the experiment by NISA (2005), the magnitude of the swirling flow in pipeline A, which is defined as the ratio of the circumferential momentum to the axial one, was 0.26 at a position three diameters upstream of the orifice of pipeline A and 0.08 at the same position in pipeline B. Since then, several studies have been conducted to elucidate the mechanism of FAC in the pipeline (Yoneda et al., 2008; Ahmed et al., 2012; Fujisawa et al., 2012; Takano et al., 2012; Utanohara et al., 2012); however, this mechanism has not yet been fully understood because of the complexity of the flow field related to the FAC. It should be mentioned that the thinning rate of pipeline A is much higher than that on the other side and that of pipeline B. Thus, the non-axisymmetric pipe-wall thinning behind an orifice is considered a dangerous phenomenon from the viewpoint of safety management of the power plant.

One of the causes of non-axisymmetric pipe-wall thinning behind an orifice is the influence of the pipeline elements upstream, such as the elbow and the tee junction. Therefore, the influence of

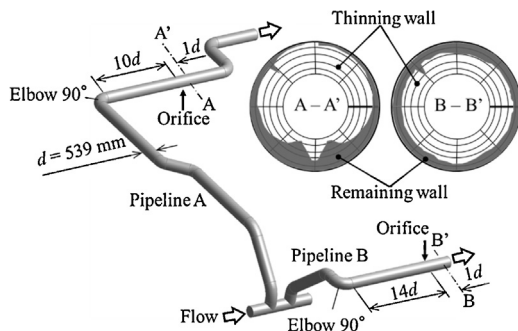


Fig. 1. Pipeline layout of Mihama power plant.

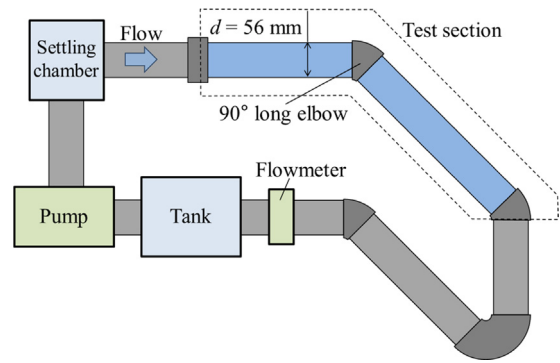


Fig. 2. Experimental setup.

the elbow on the wall thinning behind an orifice in a swirling flow was studied by Takano et al. (2013) in a preliminary experiment through measurement of the mass transfer rate behind the orifice by a benzoic acid dissolution method. The result of this experiment demonstrated that the mass transfer distribution downstream of the orifice is enhanced owing to the combined effect of the elbow and swirling flow. However, details of the velocity field and the mass transfer rate downstream of the elbow and orifice have not yet been fully understood.

The objective of this study is to understand the complex mechanism of the non-axisymmetric wall thinning that occurs downstream of an orifice through measurement of the velocity field by stereo particle image velocimetry (stereo PIV) and measurement of the mass transfer rate by the benzoic acid dissolution method. These measurements are performed at various positions in the pipeline with the elbow and orifice with and without the swirling flow in the upstream.

2. Experimental apparatus and procedures

2.1. Experimental setup

The experimental study on the velocity field and the mass transfer characteristics in the pipeline with the elbow and orifice with and without swirling flow was conducted in a closed-circuit water tunnel (Fujisawa et al., 2012). A schematic layout of the water tunnel is shown in Fig. 2. It consists of a pump, settling chamber, honeycomb, flow-developing section, and test section of the pipeline, in which the measurements of the velocity field and mass transfer rate were conducted by stereo PIV and the benzoic acid dissolution method, respectively. Fig. 3 shows details of the test

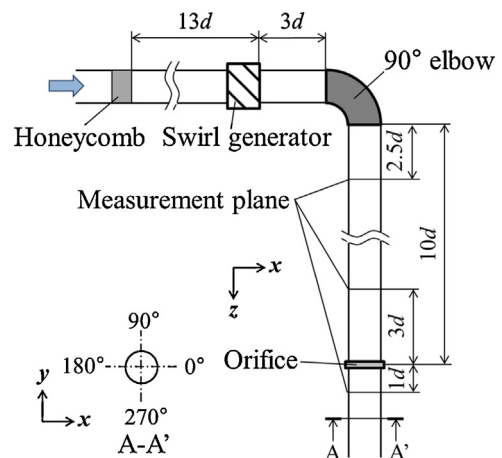


Fig. 3. Details of experimental test section.

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