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Experimental and numerical studies on mass transfer characteristics behind an orifice in a circular pipe for application to pipe-wall thinning

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ABSTRACT

Experimental and numerical studies are carried out to understand the mass transfer characteristics in a circular pipe behind an orifice, which is often encountered in pipe-wall thinning due to flow accelerated corrosion in pipelines of nuclear/fossil power plants. The measurement of mass transfer coefficient is conducted by using benzoic acid dissolution method in a water flow, which allows the measurement of mass transfer behind the orifice in a circular pipe at the Schmidt number near the actual operating condition of the pipeline. The measurement of mass transfer coefficient behind the orifice shows a maximum Sherwood number in the region 1–2 pipe diameters downstream of the orifice due to the flow turbulence, and it decreases gradually in the downstream, which agrees qualitatively with the feature of pipe-wall thinning in the pipeline in literature. The present result indicates that the Sherwood number behind the orifice is greatly increased by increasing the Schmidt number and the Reynolds number, though the geometrical factor, which is the ratio of the thinning rate of the orifice flow with respect to that of the fully developed pipe flow, is weakly dependent of these parameters. It is also found that the experimental Sherwood number profiles and the mean velocity distribution behind the orifice are well reproduced in the numerical simulation by the k–ε model with the empirical modification of high-Schmidt-number flows, though the maximum Sherwood number is slightly overpredicted, reflecting the higher prediction of turbulence energy behind the orifice. These results demonstrate the usefulness of the numerical simulation for predicting the pipe-wall thinning due to the flow accelerated corrosion in the orifice flow.

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1. Introduction

Pipe-wall thinning in a circular pipe is one of important topics encountered in the maintenance and the safety management of the pipelines in nuclear/fossil power plants. The mechanism of the wall thinning in the pipeline is known to be caused by the flow accelerated corrosion [1–4], which is the complex physical and chemical phenomenon accelerated by the flow turbulence, under the influence of temperature, pH of the fluid and the material properties of the pipeline.

The pipeline rupture accident occurred in Mihama nuclear power plant in 2004, which is known as a typical accident caused by the flow accelerated corrosion. The pipe-wall thinning due to the corrosion occurs strongly downstream of the orifice in 1–2 diameter of the pipeline behind the orifice [5]. Since then, experimental and numerical studies are carried out mainly from the fluid mechanical aspect of the flow behind the orifice [6–12]. These studies showed that the flow reattached on the pipe wall in 2–3 diameter downstream of the orifice, while the maximum pipe-wall thinning rate was observed in the near center of the recirculating flow region in 1–2 diameter downstream of the orifice, where the highly turbulent flow exists. It was also reported that the downstream variations of the pipe-wall thinning behind the orifice is well correlated with the turbulence energy [13] and the fluctuating wall-shear-stress in the flow [14]. The pipe-wall thinning phenomenon due to the flow accelerated corrosion is now considered as the mass transfer phenomenon of the ferrous ions from the wall materials of carbon steel to the bulk flow [13–16]. This is consistent with the theoretical consideration of the pipe-wall thinning from the point of corrosion [3].

The mass transfer coefficient of the flow behind the orifice was measured by the electrochemical method [2,17] and by the naphthalene sublimation method [18,19] in literature. The former method allows the measurement of mass transfer coefficient of the carbon steel materials in water flow at high Schmidt number $Sc = 1460$ in the temperature $T = 293$ K, while the mass transfer coefficient is measured by the latter method in the air flow at low Schmidt number $Sc = 2.3$. Both results of mass transfer rate

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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)
c_n	concentration at at first grid point from the wall (kg/m^3)
c_μ	constant (–)
D	molecular diffusion coefficient (m^2/s^2)
d	pipe diameter (m)
J_w	mass flux at wall (kg/(m^2 s))
k	turbulent energy (m^2/s^2)
K	mass transfer coefficient (m/s)
K_0	mass transfer coefficient in straight pipe flow (m/s)
Re	Reynolds number (=Ud/ν) (–)
Sc	Schmidt number (=ν/D) (–)
Sc_t	turbulent Schmidt number (–)
Sh	Sherwood number (=Kd/D) (–)
$Sh_{\max}$	maximum Sherwood number (–)
St_m	Stanton number for mass transfer (=K/U) (–)
U	mean velocity at inlet (m/s)
U_τ	friction velocity (m/s)
u^i	velocity components (m/s)
x_i	coordinate (m)
$\delta h/\delta t$	wall thinning rate (m/s)
ε	dissipation rate (m^2/s^3)
κ	Karman constant (–)
ν	kinematic viscosity of fluid (m^2/s)
ν_t	eddy viscosity (m^2/s)
ρ	density of water (kg/m^3)
ρ_B	density of benzoic acid (kg/m^3)

Superscript

+	non-dimensional value by friction velocity
–	mean component of flow variables

show similar profiles behind the orifice, and they show the maximum in 1–2 pipe diameters behind the orifice. Although these features of mass transfer rate are qualitatively reproduced in the actual thinning rate behind the orifice in the actual pipelines [5], the magnitude of the Sherwood number of the flow behind the orifice may be deviated from the actual thinning rate due to the influence of Schmidt number and Reynolds number. The Schmidt number of the flow in the actual pipelines is expected to be 30–100, which is mainly due to the high temperatures of the flow and the wall material of carbon steel. Therefore, it is important to study the influence of Schmidt number and Reynolds number on the mass transfer rate of the flow behind the orifice.

In order to understand the mass transfer characteristics behind the orifice, the numerical simulation has been carried out in literature, and several numerical models have been studied to predict the mass transfer coefficient downstream of the orifice. Uchida et al. [20] proposed a numerical simulation using a standard k–ε model of turbulence with a wall function approach for determining the mass flux through the wall with the Prandtl–Taylor analogy. However, the detail comparison with the flow behind the orifice has not been reported. Later, Xiong et al. [11] examined the mass transfer characteristics behind the orifice using the low-Reynolds-number version of k–ε models, which allow the determination of the mass flux through the wall directly from the concentration gradient at the wall. Among various low-Reynolds-number k–ε models, the model proposed by Abe et al. [21] provides closer results to the experimental data of abrupt contraction and expansion flow [2]. Although the numerical simulation based on the low-Reynolds-number k–ε model [21] provides closer results to the mass transfer measurements, some of the predictions diverge largely from the experimental data due to the influence of the turbulence models [11]. This suggests the difficulty for predicting the mass transfer coefficient behind the orifice in the pipeline, even if the low-Reynolds-number versions of k–ε models are used. It should be mentioned that the turbulence model proposed by Abe et al. [21] was also tested to some orifice flows, and the influence of the orifice to pipe diameter ratio on the mass transfer rate behind the orifice was numerically examined by El-Gammal et al. [12] and Ahmed et al. [13]. The validation of the numerical result was carried out by the pipe-wall-thinning of hydrocal material to simulate the flow accelerated corrosion [13]. On the other hand, there is a strong demand from the practical application to predict the mass transfer rate of the flow behind an orifice using a high Reynolds number version of k–ε model, which does not require fine meshes to resolve the near-wall region, because the near-wall boundary condition can be applied to the region in logarithmic law of the wall. This point becomes more important for predicting the wall thinning in the actual pipelines of high-Reynolds-number flows, where the velocity gradient is very steep near the wall.

In this paper, the mass transfer phenomenon behind an orifice in a circular pipe is studied experimentally by using the benzoic-acid dissolution method, which allows the measurement of the mass transfer coefficient in the Schmidt number range close to the actual pipelines. Furthermore, the numerical simulation is carried out using the k–ε model of turbulence employing the empirical formula for high-Schmidt-number flows to examine the prediction method on the pipe-wall thinning of the flow behind the orifice.

2. Experimental apparatus and procedure

2.1. Experimental method

Fig. 1 shows a schematic diagram of water tunnel apparatus for the measurement of mass transfer in a circular pipe behind an orifice. The experimental apparatus consists of a pump, a settling chamber, a straight pipe, and an orifice, which is followed by a test section for the measurement of mass transfer coefficient behind the orifice. The flow rate was measured by an electro-magnetic flow meter located in the downstream of the test section. The flow

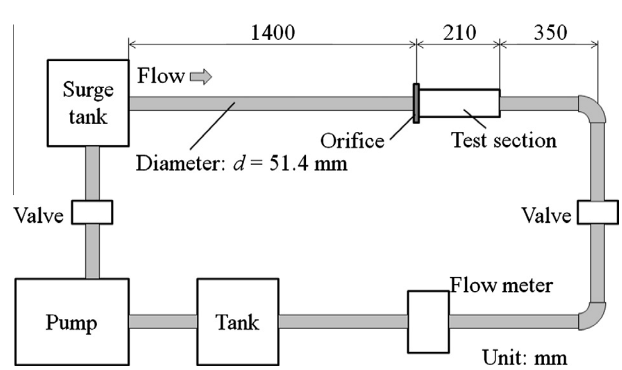

Fig. 1. Experimental setup.

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