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Mass transfer measurements on periodic roughness in a circular pipe and downstream of orifice

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ABSTRACT

This paper describes the mass transfer characteristics on periodic roughness in a circular pipe and that downstream of an orifice. The mass transfer enhancement ratio of the rough pipe with respect to the smooth pipe are measured by the plaster dissolution method for various combinations of roughness height and wavelength of the periodic roughness, and the influence of roughness on the mass transfer enhancement is examined experimentally. The mass transfer enhancement on periodic roughness is highly increased with increasing the roughness parameter, defined by the roughness height to the wavelength. It is found that the mass transfer enhancement of rough pipe is more than 2 times larger than that of the smooth pipe, which is due to the formation of the local recirculating region over the periodic roughness. On the other hand, minor mass transfer enhancement is observed on the flow downstream of an orifice. The examination of the flow and mass transfer over the periodic roughness and that downstream of orifice is carried out by the numerical simulation with low-Reynolds number k–ε model. The result indicates that the formation of local recirculating region on the periodic roughness is the major source of mass transfer enhancement on the rough pipe, while the minor mass transfer enhancement downstream of the orifice is attributed to the effect of separating shear layer originating from the orifice edge on the wall, which is dominant over the local effect of recirculating flow on the periodic roughness downstream of the orifice.

1. Introduction

The wall thinning of the pipeline in nuclear/fossil power plants is an important topic of interest to maintain the safety management of the pipelines in the power plants. The wall thinning in the pipeline is known to be caused by the flow accelerated corrosion (FAC), which is the corrosion phenomenon of the carbon-steel pipeline under the influence of turbulent flow. The phenomenological observation of the FAC is the mass transfer process of the iron ions in the wall material diffusing into the turbulent bulk flow through the oxide layer on the wall material, which is influenced by the chemical reaction of the wall material with the bulk flow. The FAC is known as a mass transfer phenomenon driven by the concentration gradient of the iron ions on the wall, while it is highly accelerated by the turbulence in the flow field [1,2]. Therefore, the wall-thinning rate is highly influenced by the turbulent flow, while it is also affected by the water chemistry of the wall materials in high temperature water and the oxide layer generated on the wall materials [2–5]. This makes the physical phenomenon of wall thinning more complex.

The FAC is often occurs in the pipeline with highly turbulent flows, such as the flow downstream of the orifice, elbow and tee junction of the pipeline, so that there are many phenomenological observation of the pipeline flow in literature [6–20]. These observation contributes to further development of the FAC models, which will be useful in predicting the status of pipe-wall thinning in the prototype pipeline by numerical simulations.

Surface roughness plays an important role in the fluid mechanics of pipeline flows, while the roughness effect on the mass transfer characteristics is not so well understood in literature in comparison with that of the friction loss in a pipe. The effect of roughness on the momentum transfer has been studied on the sand-grain roughness in a pipe and the pressure drop was measured on the rough pipe. As long as the wall is hydraulically smooth, where the non-dimensional roughness height is less than 5, there is no effect of roughness on pressure drop. With increasing the roughness height, the pressure drop increases and finally a fully rough condition is reached, where the friction factor becomes independent of the Reynolds number [21]. In order to understand

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Nomenclature

c	concentration [kg/m^3]	k	turbulent energy [m^2/s^2]
c_b	concentration in bulk flow [kg/m^3]	Re	Reynolds number (=Ud/ν) [–]
c_w	concentration at wall [kg/m^3]	t	elapsed time [s]
d	pipe diameter [mm]	U	bulk velocity [m/s]
h	height of periodic roughness [mm]	x, y	streamwise and wall-normal coordinates [mm]
K_x, K_y	streamwise and normal mass transfer coefficient [m/s]	x'	streamwise coordinate originating from negative to positive change of wall height [mm]
$\overline{K_x}$, $\overline{K_y}$	mean mass transfer enhancement ratios [–]	y^+	wall-normal coordinate normalized by friction velocity
$\overline{K_{xm}}$, $\overline{K_{ym}}$	mean mass transfer enhancement ratios [–]	$\delta h_x/\delta t$	streamwise thinning rate [mm/s]
$\overline{K_x}_{\max}$, $\overline{K_y}_{\max}$	maximum of mean mass transfer enhancement ratios [–]	$\delta h_y/\delta t$	wall-normal thinning rate [mm/s]
$\overline{K_x}'$, $\overline{K_y}'$	RMS mass transfer enhancement ratios [–]	λ	wavelength of periodic roughness [mm]
$\overline{K_x}'_{max}$, $\overline{K_y}'_{max}$	maximum of RMS mass transfer enhancement ratios [–]	ν	kinematic viscosity of fluid [m^2/s]
		ρ	density of water [kg/m^3]
K_0	mass transfer coefficient in smooth pipe [m/s]	ρ_b	density of plaster [kg/m^3]

the effect of roughness on mass transfer characteristics, the measurement of mass transfer coefficient on the rough pipe has been carried out in literature [22–24]. The results indicate that the mass transfer enhancement through the V-shaped rough pipe is three times higher than of the smooth pipe, while the result depends greatly on the roughness height, Reynolds number and Schmidt number of the flow. Therefore, the influence of the roughness may not be neglected in the wall-thinning prediction of the pipeline, while it may be important in the prediction.

The wall-thinning due to FAC is often associated with the formation of scallop on the pipe wall, which is a periodic dissolution roughness on the pipe wall [25–32]. Such a periodic roughness on the pipe wall is often observed in the highly dissolved wall of the pipe, such as the wall downstream of an orifice. The appearance of scallop may magnify the mass transfer from the pipe wall, while little is known about the influence of the periodic roughness on the mass transfer characteristics. The scallop is expected to be generated on the pipe wall by the flow near the rough surface, which consists of the flow separation from the crest of the roughness element and the following formation of the recirculating flow back to the crest along the wall [25], which is illustrated in Fig. 1. The turbulent transition of the separated flow from the crest may generate high mass transfer coefficient on the wall due to the impingement of the flow [25], which may bring about the high thinning rate of the pipe wall.

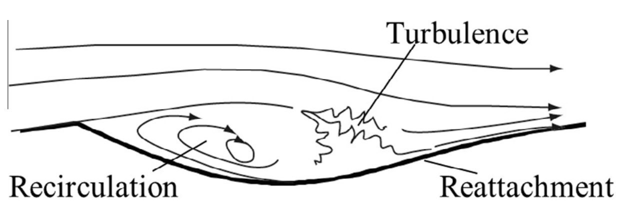

Fig. 1. Illustration of flow over a scallop [25].

Recently, Hammer et al. [32] carried out numerical simulation of the flow over a periodic dissolution roughness using k–ε model of turbulence combined with the mass and momentum transfer equation, and they reported the formation of the recirculating region downstream of the crest of the roughness and the high mass transfer on the leeward of the trough. However, the details of the mechanism have not been fully understood. Therefore, further study on the mass transfer measurement of the periodic roughness is an important issue for the pipe-wall thinning problems.

The purpose of this paper is to study the influence of the periodic roughness on the mass transfer characteristics of the flow through a rough circular pipe and those downstream of an orifice by measuring the mass transfer coefficient using the plaster dissolution method. Furthermore, the mechanism of mass transfer enhancement is studied by numerical simulation of the flow and mass transfer over the periodic roughness in a pipe.

2. Experimental methods

The experiments were carried out in a water tunnel having a circular cross-section of a pipe of 56 mm in diameter, which is illustrated in Fig. 2. The water tunnel consists of a pump, settling

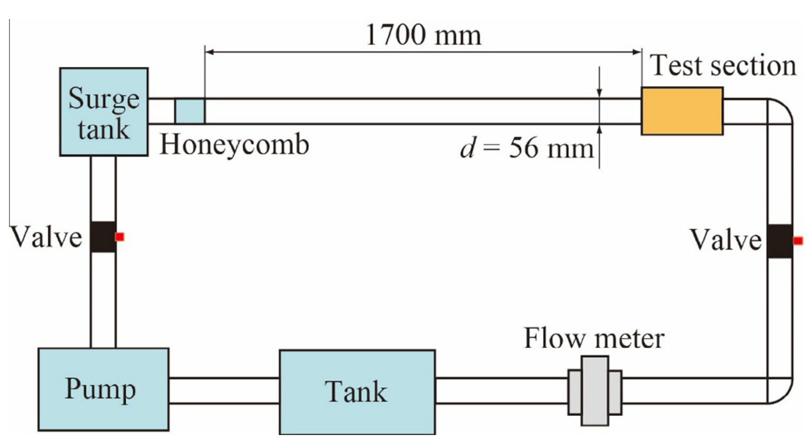

Fig. 2. Schematic layout of water tunnel.