International Journal of Heat and Mass Transfer 92 (2016) 394–402

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Influence of swirling flow on mass and momentum transfer downstream of a pipe with elbow and orifice

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 6 July 2015
Accepted 25 August 2015
Available online 15 September 2015

Keywords:
Mass transfer coefficient
Turbulent energy
Swirling flow
Elbow
Orifice
Pipe-wall thinning

ABSTRACT

The influence of swirling flow on mass and momentum transfer downstream of a pipe with elbow and orifice is studied experimentally. The experiments are carried out in the pipe at Reynolds number $Re = 3 \times 10^4$ for various magnitudes of swirl intensity up to 0.9 driven by the rotary swirler. The mass transfer coefficient and the cross-sectional velocity field downstream of the orifice are measured by the plaster dissolution method and the stereo PIV, respectively. It is found that the mass transfer coefficient and the turbulent energy increases gradually with increasing the swirl intensity, while they become non-axisymmetric downstream of the orifice for the swirl intensity larger than 0.6 at the inlet of the elbow, which is followed by the saturation at higher swirl intensity. The maximum mass transfer coefficient is found to have a peak at one diameter downstream of the orifice and it reaches 6 times larger value than that of the straight pipe without swirling flow. The behavior of the maximum mass transfer coefficient with respect to the swirl intensity is similarly observed in the near-wall turbulent energy.

1. Introduction

The mass and momentum transfer in flow through a circular pipe downstream of an orifice is an important topic of interests for fundamental and practical studies in the field of thermal and fluid engineering. The example of this flow configuration is found in the pipe-wall thinning of a pipeline in nuclear/fossil power plant, which is one of the industrial problems of the pipeline led to the pipeline break accident. The pipe-wall thinning is mainly caused by the flow accelerated corrosion (FAC), which is the corrosion phenomenon of the carbon-steel pipe wall, where iron ions of the wall diffuse into the turbulent bulk flow through the oxide layer over the wall surface [1–3]. The FAC is often occurs in the pipeline with highly turbulent flows, such as the flow downstream of orifice, elbow and tee junction of the pipeline, so that the control and the prediction of FAC are important topics in the safety management of the power plants [4–10]. Although FAC is affected by the water chemistry, the wall-thinning rate is considered as a mass transfer phenomenon driven by the concentration gradient of the iron ions on the wall surface and that in the bulk flow [2].

One of the important topics of research in FAC is the non-axisymmetric pipe-wall thinning on the pipe downstream of an orifice, which leads to the pipeline break accident, as observed in the Mihama nuclear power plant in 2004. The pipeline consists of the elbow, the straight pipe of 10 diameter long and the orifice, as illustrated in Fig. 1. The pipe-break accident in the Mihama case is known to be due to the FAC occurring immediate downstream of the orifice. According to the experiment by NISA [11], the swirling flow was observed in the pipeline arising from the complex pipeline geometry upstream of the pipeline-break section. The swirl intensity of the flow, defined by the ratio of the circumferential momentum to the axial one, is estimated as 0.26 at 3 diameters upstream of the orifice. Since then, several experimental studies on the mass and momentum transfer downstream of the orifice have been carried out to elucidate the mechanism of pipe-wall thinning in the pipeline [12–22].

Recent studies on the measurement of mass transfer coefficient downstream of the orifice in swirling flow are conducted in a water tunnel and found that the pipeline elements upstream of the orifice modify the characteristics of mass and momentum transfer [17,20–22]. Although these experiments provide important findings, such as the occurrence of non-axisymmetric mass transfer downstream of the orifice, the influence of the swirl on the mass and momentum transfer downstream of the orifice is still not clear. This is mainly due to the single value of swirl intensity studied in the experiments.

The purpose of this paper is to investigate the influence of swirl on the mass and momentum transfer downstream of the pipe with elbow and orifice for various swirl intensities by measuring the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.087
0017-9310/

Nomenclature

c	concentration [kg/m^3]
c_b	concentration in bulk flow [kg/m^3]
c_w	concentration at wall [kg/m^3]
d	pipe diameter [m]
K	mass transfer coefficient [m/s]
K_0	mass transfer coefficient in straight pipe [m/s]
k	turbulent energy [m^2/s^2]
R:	pipe radius [m]
r:	radial distance from pipe center [m]
Re	Reynolds number (=Ud/ν) [–]
S	swirl intensity, Eq. (1) [–]
U	bulk velocity [m/s]
u_x, u_y, u_z	mean velocity components in x, y, z directions, respectively [m/s]
u_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 plaster [kg/m^3]
θ	circumferential angle

mass transfer coefficient and the velocity field by plaster dissolution method and stereo particle image velocimetry (PIV), respectively.

2. Experimental apparatus and procedures

2.1. Experimental set-up

The experimental studies on mass and momentum transfer downstream of a pipe with elbow and orifice under the influence of swirling flow have been carried out in a closed-circuit water tunnel. A schematic layout of the water tunnel is shown in Fig. 2. Note that the water tunnel consists of a pump, settling chamber, flow straightener, rotary swirler, orifice and the test section. It should be mentioned that the length of the straight pipe between the elbow and the orifice is set to 10d to meet the condition of Mihama plant [11], where d is a pipe diameter. The diameter of the pipe is set to d = 56 mm and the radius to diameter ratio of the elbow is 1.2. The test section is reversible for the measurements of mass transfer coefficient and velocity field, which are carried out by the plaster dissolution method and stereo PIV, respectively.

The swirling flow was generated by a rotary swirler, which is illustrated in Fig. 3. The rotary swirler consists of a honeycomb and AC servo motor, which are connected by a timing belt [23]. The AC servo motor drives the rotation of the shaded section of the pipe, where the honeycomb is fixed inside the pipe. Note that the peripheral diameter of the honeycomb element is 3.2 mm with 30 mm long. The rotary swirler allows the solid rotation of the honeycomb in peripheral direction, while the axial velocity distribution is made uniform by the function of the honeycomb structure. Therefore, the magnitude of the swirl intensity, which is the ratio of the circumferential momentum to the axial one [24], can be evaluated in a simple form as follows;

$$S = \int_0^R u_z u_\theta r^2\, dr \Big/ \left(R \int_0^R u_z^2 r\, dr \right) = \frac{1}{2} R\omega/U \tag{1}$$

where R is the radius of a pipe, r is the radial distance from a pipe axis, u_z is the streamwise mean velocity and u_θ is the circumferential mean velocity. Eq. (1) indicates that the swirl intensity can be evaluated directly from the angular velocity ω of the rotary swirler, the radius R of the pipe and the bulk velocity U of the flow through the pipe.

The pipe with elbow and orifice was set to 7d downstream of the rotary swirler. Note that the diameter ratio of the orifice is set to 0.6 and the temperature of the working fluid water is kept at 303 K during the experiment. Therefore, the Reynolds number of the flow based on the diameter of the pipe was set to Re (=Ud/ν) = 3 × 10^4, so that the flow is in a turbulent state.

2.2. Measurement of mass transfer coefficient by plaster dissolution method

The distribution of the mass transfer coefficient downstream of the orifice was measured by the plaster dissolution method [12]. For this to be done, an aluminum test section for the measurement of mass transfer coefficient is prepared and set downstream of the orifice, which is shown in Fig. 4. Note that the plaster layer is 194 mm long with 3 mm in thickness. The merit of this plaster dissolution method is non-detrimental nature of the material, while the benzoic acid used in our previous experiment [17] may suffer from the health harmful gas in the casting process of the liquid benzoic acid at high temperatures. In the preparation of the solid layer of plaster on the pipe wall, the liquid plaster is casted into each half-pipe of the test section using the aluminum cylindrical guide of 56 mm in diameter. It should be mentioned that the gas bubbles generated in the plaster layer are removed using the vacuum pump. The experimental arrangement for measuring the surface-depth distribution on the plaster layer is shown in Fig. 4. The depth distribution is detected by a laser displacement sensor having a spatial resolution of 1 μm (LK-030,

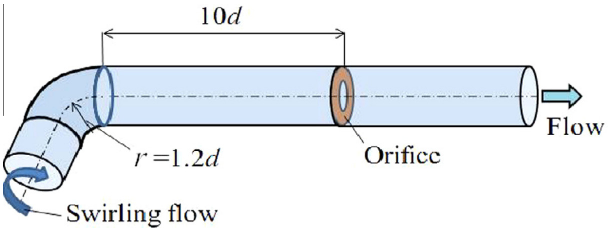

Fig. 1. Pipeline layout of Mihama plant.

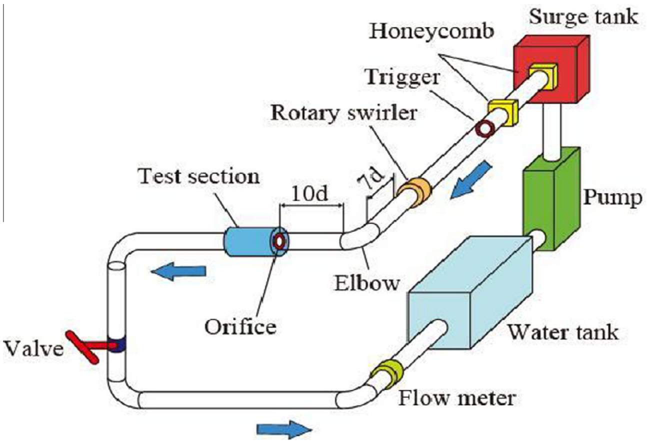

Fig. 2. Schematic layout of water tunnel.