Annals of Nuclear Energy 80 (2015) 356–364

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Non-axisymmetric wall-thinning downstream of elbow–orifice pipeline in swirling flow

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ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form 15 January 2015
Accepted 20 January 2015
Available online 26 February 2015

Keywords:
Pipe-wall thinning
Elbow
Orifice
Swirling flow
POD
Turbulent energy

ABSTRACT

The non-axisymmetric wall-thinning leading to a pipeline break is studied in a scaled model experiment in a water tunnel. The pipeline consists of an elbow, an orifice and a straight pipe between them. The measurement of velocity field is carried out downstream of the orifice using stereo PIV and the spatial correlation of velocity fluctuations is analyzed by snapshot Proper Orthogonal Decomposition (POD), while the mass transfer coefficient is measured by a benzoic acid dissolution method. These measurements are carried out at Reynolds number $Re = 3 \times 10^4$ with and without swirl. It is found that the non-axisymmetric flow and mass transfer is found downstream of the orifice due to the combined influence of the secondary flow in the elbow and the swirling flow. The POD analysis indicates that non-axisymmetric velocity field is generated in the first two POD modes, which suggests the structural change in the velocity field downstream of the orifice, such as the non-axisymmetric growth of the velocity and turbulent energy in the lower POD modes. It is also found that the near-wall turbulent energy distribution is correlated with the measurement of mass transfer coefficient.

1. Introduction

The pipe-wall thinning in nuclear/fossil power plants is one of the important topics of interest in the safety management of the power plants. The pipe-wall thinning is mostly occurred by the flow accelerated corrosion (FAC), which is a turbulent diffusion phenomenon of the wall materials of carbon steel into the turbulent bulk flow through the oxide layer over the wall surface. Although FAC is affected by the temperature, pH and oxygen concentration of the fluid flow and also by the chromium concentration in the carbon-steel of the wall material, it can be considered as the mass transfer phenomenon driven by the concentration gradient of the iron ion on the carbon steel and that in the bulk flow. The FAC phenomenon often occurs in the pipeline in highly turbulent flows, such as the flow downstream of orifice, elbow and T junction of the power plants, so that the control of FAC is an important technology in the safety management of the nuclear/fossil power plants (Keller, 1974; Sanchez-Caldera, 1984; Dooley, 2008; Yoneda et al., 2008; Hwang et al., 2009; Ahmed, 2010; Uchida et al., 2011; Ahmed et al., 2012; Pietralik, 2012; Utanohara et al., 2012; Lin and Ferng, 2014).

Pipeline break accident due to FAC happened in the Mihama nuclear power plant in 2004. The pipeline consists of an elbow, a straight pipe and an orifice, and the pipeline break occurs immediate downstream of the orifice. The pipeline geometry is illustrated in Fig. 1. According to the scaled model experiment, the swirling flow was observed in the pipeline (NISA, 2005). The swirl intensity of the flow, which is defined by the ratio of the circumferential momentum to the axial one, is estimated as 0.26 at 3 diameters upstream of the orifice. One of the causes of the swirling flow generation is expected to be due to the three-dimensional configuration of the pipeline (Yuki et al., 2011). Since then, some experimental studies on the mass transfer characteristics downstream of an orifice in the swirling flow have been carried out to elucidate the mechanism of non-axisymmetric pipe-wall thinning in the pipeline. One of the causes of the non-axisymmetric wall-thinning downstream of the orifice is the orifice bias error (Ohkubo et al., 2011; Fujisawa et al., 2012), which triggers the asymmetry of the flow downstream of the orifice due to the minor pipeline diameter error of the standard pipe, which is known to be 0.8% of the diameter in the Japanese Industrial Standard (JIS G3456). Due to the unstable nature of the flow downstream of the orifice in the swirling flow, the distribution of mass transfer coefficient is enhanced non-axisymmetrically downstream of the orifice. The critical bias error is found to be 0.4% of the pipe diameter for the swirl intensity larger than 0.2 (Takano et al., 2012).

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http://dx.doi.org/10.1016/j.anucene.2015.01.043
0306-4549/

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]
d	pipe diameter [m]
K	mass transfer coefficient [m/s]
K_0	mass transfer coefficient of straight pipe [m/s]
k	turbulent energy [m^2/s^2]
N	number of instantaneous velocity fields
R	pipe radius [m]
r	radial distance from pipe center [m]
Re	Reynolds number (=Ud/ν) [–]
S	swirl intensity, Eq. (7) [–]
Sc	Schmidt number (=ν/D) [–]
U	bulk velocity [m/s]
U_τ	friction 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]
Greeks	
$\delta h/\delta t$	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]

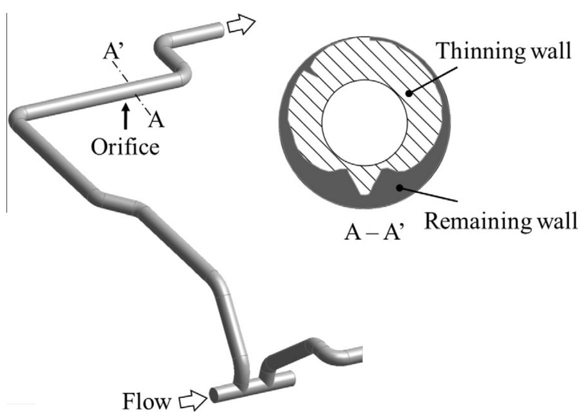

Fig. 1. Pipeline layout of Mihama plant.

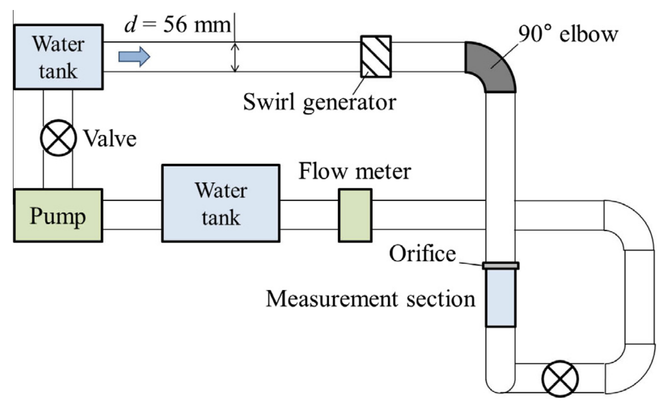

Fig. 2. Experimental setup.

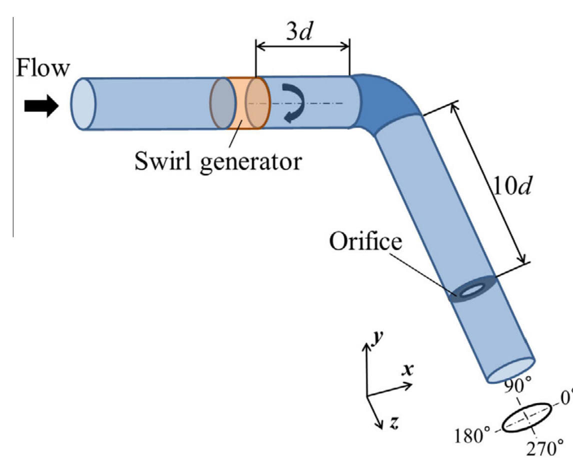

Fig. 3. Details of experimental test section.

More recent study on the mass transfer characteristics downstream of the orifice suggests that the influence of the elbow upstream of orifice is crucial on the formation of non-axisymmetric mass transfer coefficient distribution (Takano et al., 2013). However, the details of the non-axisymmetric characteristics of the flow and mass transfer downstream of the elbow–orifice pipeline have not been fully understood yet.

The purpose of this paper is to understand the non-axisymmetric wall-thinning downstream of an elbow–orifice pipeline by the measurements of velocity field using the stereo particle image velocimetry (stereo PIV) combined with the snapshot POD and the mass transfer measurement by the benzoic acid resolution method. These measurements are carried out in the pipeline geometry with elbow and orifice and with and without the swirling flow.

2. Experimental apparatus and procedures

2.1. Experimental set-up

The experimental study on the velocity field and the mass transfer characteristics downstream of an elbow–orifice pipeline with and without swirling flow has been carried out in a closed-circuit water tunnel. A schematic layout of the water tunnel is shown in Fig. 2. The water tunnel consists of a pump, a settling chamber, a flow developing section and swirl generator before entering into the elbow–orifice pipeline. Fig. 3 shows the details of the test section, which consists of an elbow, a straight pipe, an orifice and the following straight-pipe section, where the measurements of velocity field and the mass transfer coefficient are carried out using the stereo PIV and the benzoic acid dissolution method, respectively. It should be mentioned that the length of the straight pipe between the elbow and the orifice is set to 10d to meet with the condition of Mihama nuclear plant (NISA, 2005), where d is a pipe diameter. The experimental diameter of the pipe is d = 56 mm and the radius to diameter ratio of the elbow is 1.2.