Annals of Nuclear Energy 88 (2016) 151–157

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Attenuation of wall-thinning rate in deep erosion by liquid droplet impingement

Nobuyuki Fujisawa [a,*], Takayuki Yamagata [a,*], Keitaro Wada [b]

[a] Visualization Research Center, Niigata University, 8050, Ikarashi 2-Nocho, Nishi-ku, Niigata 950-2181, Japan
[b] Graduate School of Science and Technology, Niigata University, 8050, Ikarashi 2-Nocho, Nishi-ku, Niigata 950-2181, Japan

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 7 September 2015
Accepted 21 October 2015
Available online 14 November 2015

Keywords:
Wall thinning
Liquid droplet impingement
Erosion
Erosion model
Power plant
Pipeline

ABSTRACT

This paper describes an experimental study on the wall-thinning rate in deep erosion by liquid droplet impingement (LDI) in a pipeline for application to nuclear/fossil power plant. The experiment is carried out in a spray jet apparatus, which allows the evaluation of local wall-thinning rate by the LDI erosion. The surface contour of erosion and the wall-thinning rate are measured and the observation by scanning electron microscope (SEM) is carried out in this experiment. The experimental result indicates that the wall-thinning rate is highly attenuated and the macro structure on the erosion surface grows with an increase in the erosion depth, which is due to the influence of the liquid film over the erosion surface. The erosion model for predicting the wall-thinning rate in deep erosion is proposed by introducing the attenuation factor with a function of erosion depth. The introduction of attenuation factor with liquid-film effect shows a better correlation with the experimental data, and the accuracy of correlation is improved by a factor of 2.

1. Introduction

Liquid droplet impingement (LDI) erosion is one of the causes of pipeline damage in nuclear/fossil power plants. The mechanism of the LDI erosion has been investigated experimentally and numerically both from the points of plant engineering and flow physics in literature. The fundamental of the LDI erosion is a single droplet impact on solid surface and the physics of the droplet impact has been studied by Field et al. (1985) using the high-speed observation of gelatin impact. The result indicates that the shock wave is generated at the instant of droplet impact on the solid wall, which propagates through the liquid medium and reflects at the free surface of the droplet and the reflected pressure wave focuses near the wall material leading to the occurrence of cavitation, while the droplet impact produces a side jet along the wall in radial direction. The side jet produces a thin film of liquid flowing over the wall with much faster velocity than that of the impact velocity of the liquid droplet. In spite of such a complex phenomenon of liquid droplet impingement on a wall, the impact pressure of the droplet roughly approximated by the impact formula, which indicates that the impact pressure is proportional to the products of the droplet density, acoustic velocity and droplet velocity (Heymann, 1969; Rochester and Brunton, 1974). The result implies that the impact pressure is independent of the droplet diameter and becomes larger than the yield stress of the carbon steel, when the droplet velocity is above 100 m/s. This condition applies to the flow through the pipeline of nuclear/fossil power plant. Therefore, the main cause of LDI erosion in the power-plant pipeline is considered to be due to the high impact pressure of the liquid droplet in the high-speed steam flow.

In order to estimate the lifetime of the pipeline in the power plant, the prediction of the wall-thinning rate due to the LDI erosion is becoming an important topic of interests in recent years (Ferng, 2008; Li et al., 2011; Morita and Uchiyama, 2011). For this to be done, experimental erosion models are fundamental and they are summarized in Table 1, which includes Heymann (1979), Sanchez-Caldera (1984), Itoh and Okabe (1993), Oka et al. (2007), Miyata and Isomoto (2008), Isomoto and Miyata (2008), Hattori and Takinami (2010), Ishimoto et al. (2011) and Fujisawa et al. (2012a, 2013, 2015). Using these erosion models, the wall-thinning rate is evaluated from the droplet parameters, such as the droplet velocity, droplet diameter, number of droplets, and the material hardness, while the influence of the liquid-film thickness on the wall-thinning rate is found to be another important factor by the recent numerical studies of Ikohagi (2011) and Xiong et al. (2011). Later, the influence of liquid film on the wall-thinning rate is experimentally studied by Fujisawa et al. (2013),

* Corresponding authors.
E-mail addresses: fujisawa@eng.niigata-u.ac.jp (N. Fujisawa), yamagata@eng.niigata-u.ac.jp (T. Yamagata).

http://dx.doi.org/10.1016/j.anucene.2015.10.024
0306-4549/

Nomenclature

c_1, c_2, c_3	constants, Eq. (1)	q	local volume flux
d	droplet diameter	V	droplet velocity
E_d	maximum erosion depth	V_o	velocity at nozzle exit
f	attenuation factor, Eqs. (3) and (4)	V_d	non-dimensional erosion rate
H_r	relative Vickers hardness with respect to pure aluminum	V_{de}	experimental erosion rate
n	power index for droplet velocity dependency	V_{dp}	predicted erosion rate
P	pump pressure	V_{du}	uniform erosion rate, Eq. (1)
t	time	x	coordinate along spray centerline
Q_o	bulk flow rate	ρ	density of liquid
		ν	kinematic viscosity of air

Table 1
Summary of previous experiments on LDI.

	Power index n	Test method	Droplet velocity V (m/s)	Droplet diameter (μm)	Test material
Heymann (1979)	5.8 (maximum rate point)	Rotating disk	93–400 (rotating speed)	810–2000	A1100-0, A6061-T6, Ni270, SUS316
Itoh and Okabe (1993)	6–8 (terminal stage)	Rotating disk	400,480 (rotating speed)	195–269 immersion drop sampling method	12 Cr steel, cobalt base alloy, titanium alloy
Isomoto and Miyata (2008), Miyata and Isomoto (2008)	6 (<100 m/s) 2 (>150 m/s)	Spray	40,300 (impact force)	20–200 immersion drop sampling method	A5083, SS400, SUS410 J1, SUS304 SK3
Hattori and Takinami (2010)	6.0–7.4 (maximum rate stage)	Water jet	80–184 (nozzle pressure)	60–120	S15C, STPA24, SUS304
Fujisawa et al. (2012a)	7 (maximum rate point)	Spray	130–160 (PIV)	60–120 shadowgraph	A1050
Fujisawa et al. (2013)	6.6 (terminal stage)	Spray	140–175 (PIV)	30 shadowgraph	A1070
Fujisawa et al. (2015)	7 (terminal stage)	Spray	140–180 (PIV)	30 shadowgraph	A1070, A5056, C3604, SS400, S20C, SUS304

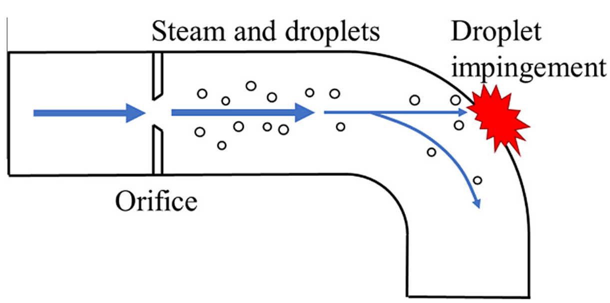

Fig. 1. LDI erosion in bent pipe downstream of orifice.

who carried out an experiment using the spray jet. They found that the wall-thinning rate is strongly attenuated by increasing the liquid-film thickness over the specimen surface. On the other hand, the wall-thinning rate has been formulated by a power law of droplet velocity with a constant power index $n = 7$, while it is scattering in a range from 3 to 8, as seen in Table 1. It should be mentioned that the power index $n = 5$ is derived from the dimensional analysis by Sanchez-Caldera (1984). Such large scattering of the power index can be explained by the influence of experimental conditions, erosion stage, material hardness, droplet diameter, liquid-film thickness and so on, while the reason of the scattering is still not clear due to the limitation of experimental study in literature (Fujisawa et al., 2012b).

The LDI erosion often occurs in a steam pipeline of the nuclear/fossil power plant, where the steam flow is highly accelerated downstream of the orifice and it impinges on the bent pipe downstream, as illustrated in Fig. 1. Once the erosion on the pipe wall is highly accelerated, the LDI erosion may cause deep erosion. This leads to a leak of the steam flow to the outside, as was the case of Onagawa power plant in 2007. In the case of deep erosion, the wall-thinning rate may be influenced by the erosion depth, while the details of such a deep erosion have not been studied in literature.

In the present study, the deep LDI erosion is experimentally studied using a high-speed spray jet for characterizing the influence of erosion depth on the wall-thinning rate. An attention is placed on the deep LDI erosion model including the influence of erosion depth.

2. Experiment

Fig. 2 shows a schematic illustration of the experimental apparatus, which consists of a straight nozzle and a pure aluminum test specimen (Al070), which is a circular plate of 40 mm in diameter with a thickness of 8 mm. The nozzle exit diameter is 0.8 mm and it generates a straight liquid column at the nozzle exit (MCP08, Ikeuchi Co.), while the liquid column changes to a spray jet immediate downstream due to the instability of the liquid-air interface associated with the entrainment of the surrounding air. The erosion experiment was carried out by impinging the jet on the test specimen from the top in the present study. Note that the erosion rate in vertical impingement agrees with that in horizontal impingement, which suggests negligibly small influence of the gravity on the erosion rate. The spray image taken by a digital camera with strobe-flush is shown in Fig. 3, which is an instantaneous spray image covering the spray jet of a distance 500 mm downstream of the nozzle exit. It is seen that the flow of liquid column is limited near the nozzle and the flow spreads almost linearly from the nozzle downstream. The detail observation of the spray jet indicates that the transition of the liquid column to the spray