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Numerical analysis on the wall-thinning rate of a bent pipe by liquid droplet impingement erosion

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ABSTRACT

This paper presents a numerical analysis of liquid droplet impingement (LDI) erosion in the pipeline of nuclear/fossil power plants. The numerical method is based on combining a Eulerian/Lagrangian computational fluid dynamics (CFD) model with an erosion model to consider various aspects of LDI erosion, such as the influence of the droplet velocity, diameter, number density, impingement angle, material hardness, liquid-film thickness, and erosion depth on the wall-thinning rate. A numerical analysis of the erosion depth distribution was carried out for the LDI erosion of a bent pipe downstream of an orifice at the Onagawa power plant incident in 2007. The results were compared with existing erosion models, and the variations in the peak erosion depths were examined. The present model results showed reasonable agreement with the prototype results at the location and the erosion depth distribution of the bent pipe. The comparison showed the importance of the liquid film and erosion depth to predicting the LDI erosion characteristics.

1. Introduction

Liquid droplet impingement (LDI) erosion is an important topic for the pipeline damage in nuclear/fossil power plants. This mechanism has been investigated in the literature both experimentally and numerically. A fundamental study on LDI erosion has shown that the impact pressure of a single droplet on a solid wall is proportional to the product of the density, acoustic velocity, and impact velocity of the droplet [1]. The impact pressure of a liquid droplet moving faster than 100 m/s has been roughly estimated to be above the yield stress of a carbon steel pipeline. Therefore, the main cause of LDI erosion in a nuclear/fossil power plant is considered to be the high-impact pressure of liquid droplets within the steam flow in a pipeline. The velocity of the steam flow is often above 200 m/s in the highly accelerated flow region, such as downstream of an orifice as illustrated in Fig. 1. The physical mechanism of LDI erosion is known to be due to a shockwave on the solid wall, which propagates through the liquid droplet and reflects onto the free surface of the droplet. This is followed by a pressure wave focused near the wall material, while the droplet impact causes a side jet of the liquid film along the wall. This is several times faster than the impact velocity of the liquid droplet [2].

LDI erosion often occurs in the steam pipelines of nuclear/fossil power plants, where the steam flow is highly accelerated downstream of the orifice and impinges on a bent pipe. Once the erosion of the pipe wall is accelerated by the liquid droplet impingement, the increased wall-thinning rate may cause steam to leak through the erosion hole outside, which can result in

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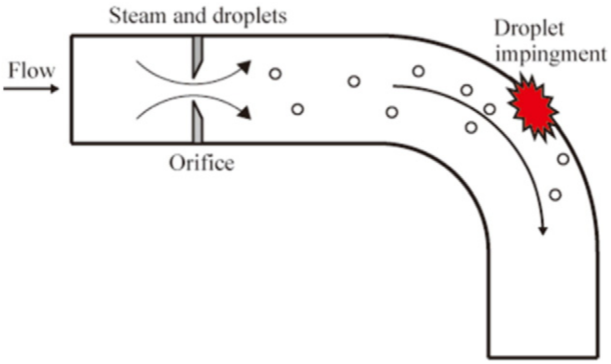

Fig. 1. LDI erosion in pipeline.

unexpected accidents with the power plant pipeline. A typical example of such steam leak occurred in a pipeline of the Onagawa nuclear power plant in 2007 [3].

In order to estimate the residual lifetime of a pipeline in nuclear/fossil power plants to ensure timely maintenance, the pipe-wall thinning due to LDI erosion is becoming an important topic of interest. In the past, several experimental studies on LDI erosion have been carried out [4–16], and erosion models have been proposed to describe the relationship between the droplet properties and wall-thinning rate. Table 1 lists some typical examples of erosion models: those of Heymann [4,5], Sanchez-Caldera [6], Isomoto and Miyata [11], Morita and Uchiyama [13], and Fujisawa et al. [15]. These erosion models are fundamental to relating the wall-thinning rate with droplet parameters such as the droplet velocity, diameter, number density, and impingement angle. Other important factors for LDI erosion are the material hardness of the pipe wall and the liquid film thickness prevailing over the pipe wall [17,18]. The former is considered in the models [11,16], and the latter is considered in the models [13,15].

In order to evaluate the wall-thinning rate of a prototype pipeline, a numerical analysis was performed using computational fluid dynamics (CFD). Ferng [19] first introduced the Eulerian/Lagrangian CFD model to predict the wall-thinning rate and applied his approach to the shell wall of feed-water heaters [20]. For flow field prediction, momentum equations combined with the k–ε model of turbulence are solved by the Eulerian model, and the Lagrangian approach is applied to predict the trajectories of the liquid droplets. The erosion model for the solid-particle impact is used to evaluate the local wall-thinning rate. A similar approach was later applied to predicting the wall-thinning rate of a bent pipe [13] by using an erosion model that considers the attenuation effect of the liquid film. Li et al. [21,22] introduced the two-way vapor-droplet coupling method to the CFD prediction model to simulate the turbulence attenuation effect in a two-phase flow. They predicted a bent pipe case by using an erosion model with a velocity dependency to the second power. A two-phase flow model [23] was introduced to predict the wall-thinning rate by accounting for the influence of the condensed droplet generation and phase change. Although these Eulerian/Lagrangian CFD models provide a qualitative method for estimating the wall-thinning rate of a pipeline due to LDI erosion, there have only been a few quantitative comparisons with the experimental results of a prototype pipeline. This may be due to the lack of a reliable erosion model applicable to the LDI erosion of a prototype pipeline.

In the present study, the LDI erosion for the bent pipe of the Onagawa power plant in the 2007 incident was studied by combining a Eulerian/Lagrangian CFD model with an LDI erosion model to consider the effects of the droplet velocity, diameter, number density, impingement angle, material hardness, liquid-film thickness, and erosion depth on the wall-thinning rate distribution. The results were compared with predictions using existing erosion models to understand the influence of the erosion model on the prediction of LDI erosion.

Table 1
Summary of typical LDI erosion models.

Reference	Erosion model	Nomenclature
[4]	$\log(Re) = 4.8\log(V) + 0.67\log(d) - \log(NER) + c_h$	A: area of droplet impingement
[6]	$dE_d/dt = c_s \rho M F_e F_h V^4 / (p^2 \varepsilon^2 A)$	c_h, c_s, c_i, c_m, c_f: constants
[11]	$dE_d/dt = c_i\, q\, H_v^{-2.75} V^2$	F_e: droplet entrainment rate
[13]	$dE_d/dt = c_m\, q H_v^{-2.75} V^2 f_m(h/d)$	F_h: hitting factor
		f_m, f_f: liquid film damping functions
		M: mass flow rate
		NER: normalized erosion resistance
[15]	$dE_d/dt = c_f\, q H_v^{-4.5} V^7 f_f(h/d)$	p: material hardness
		q: local volume flux
		Re: Volume loss per droplet
		ε: critical strain