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# Liquid droplet impingement erosion on groove roughness☆

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## ABSTRACT

A study of erosion mechanism during the liquid droplet impingement (LDI) on a rough surface was conducted using both numerical simulation and experiments. The numerical simulation was carried out for the LDI on single groove roughness utilizing the two-phase full Eulerian approach based on the high-resolution finite volume method to understand the evolution of the droplet deformation and the wall pressure distribution. The numerical results for the LDI on a large groove roughness showed that the first and the second impacts occurred close to the first contact location of the droplet on the wall, which was similar to the LDI on a smooth surface. The largest impact occurred by the third impact at the groove bottom, which was caused by the side-jet focusing and droplet focusing generated from the contact edge of the droplet. It was also found that the maximum wall pressure at the groove bottom increased with the increase in the groove roughness parameter that represented the geometrical ratio of the groove depth to the droplet diameter. In addition to the numerical studies, the erosion behavior of LDI on single groove roughness was observed experimentally using a Scanning Electron Microscope (SEM) after spray jet impingement on an aluminum specimen with various groove roughness parameter. The experimental results showed that the LDI erosion on the large groove roughness started from the groove bottom, while the LDI erosion on the small groove roughness started from the groove edge and the groove bottom. These experimental findings are well correlated with the maximum wall pressure distributions obtained from the numerical results.

## 1. Introduction

The pipe-wall thinning is often caused by the liquid droplet impingement (LDI) erosion in the pipeline of a nuclear/fossil power plant because of the continuous impingements of highly accelerated liquid droplets. The LDI erosion is often observed on the elbows, the tee junctions and the pipe walls downstream of the orifice in the pipelines where locally high flow velocity is generated, causing severe erosion in the pipeline (ASTM, 2010; JSME, 2005, 2012; Xiong et al., 2012; Naitoh et al., 2013). The mechanism of the LDI erosion is caused by the high impact pressure, which is proportional to the density, the sound speed, and the impact velocity of the droplet. Therefore, the impact pressure grows beyond the yield stress of the wall material of carbon steel, when the impact velocity becomes $> 100$ m/s, which is usually observed in the actual pipeline of a power plant. In order to evaluate the LDI erosion numerically, the Eulerian Lagrangian approach based on the momentum equation of droplets has been studied in the literature, and this has allowed the prediction of the LDI erosion combined with the empirical relation between the erosion rate and the droplet impact velocity (Ferng, 2008; Nicolici et al., 2013; Fujisawa et al., 2016).

It is known that the LDI erosion is highly influenced by the initial surface roughness during the erosion process (Hancox and Brunton, 1966; Heymann, 1970). Hancox and Brunton (1966) experimentally studied the effect of the initial surface roughness on the LDI erosion of stainless steel using a rotating arm apparatus for the erosion test, and indicated that the finer surface finish $< 10\,\mu$m had a considerable effect on the erosion rate. Heymann (1970) reported an analysis of the effect of surface roughness or irregularities found on the solid surfaces because of the machining or other influences using an electron microscope. They stated that the irregularities on the surface increased several times the force of the initial droplet impact to initiate fatigue cracks and helped the cracks to grow as a result of the radial outflow of the droplets. It is noted that the initiation of LDI erosion starts from the grain boundary of the material, which is a kind of irregularity of the material properties (Hattori and Takinami, 2010). More recently, the effect of the initial surface roughness on LDI erosion was studied experimentally using a rotating arm apparatus with the SEM (Scanning Electron Microscope) observation, indicating that the incubation period decreased with the increasing surface roughness (Kirols et al., 2015). A similar result was observed in the study of LDI erosion by spray jet

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impingement on a single groove by Fujisawa et al. (2018). They also indicated that the formation of the asperities and irregularities are accelerated on the rough surface compared to the smooth surface. However, the mechanism of LDI erosion on a rough surface is not clear owing to the geometrical complexity of the surface.

The impact pressure of a droplet on a smooth surface was theoretically studied by Heymann (1969) by two-dimensional analysis and Field et al. (1985) by cylindrical or spherical droplets. It was shown that the pressure at the contact edge can reach 3 times higher than the water hammer pressure at the droplet center. The pressure inside the cylindrical droplet is higher than in the spherical case, but edge pressure is identical for both cases. Later, the LDI phenomenon was experimentally studied by visual observation of a cylindrical droplet (Field et al., 1989), and showed that the time series deformation of droplet at the impact on the surface generated shock wave inside the droplet, and it propagated outward and reflected at the free surface, which is followed by the generation of side jet along the surface. Recently, the physics of LDI has also been studied numerically with the aid of computational fluid dynamics. Several numerical studies on the LDI were reported in literature using the two-phase Eulerian Lagrangian approach based on the Front Tracking method (Haller et al., 2002), the two-phase full Lagrangian approach based on the Moving Particle Semi-implicit method (Arai and Koshizuka, 2009; Xiong et al., 2011, 2012) and the two-phase full Eulerian approach based on the Volume of Fluid method (Li et al., 2011; Sasaki et al. 2016). These studies explored the pressure evolution during the LDI process, such as the shock wave generation, its outward propagation, reflection at the free surface and side jet formation, and showed that high impact pressure is generated at the contact edge of the droplet on the wall due to the compressibility of the liquid droplet. It is noted that the cylindrical droplet was studied by Arai and Koshizuka (2009), Xiong et al., (2011, 2012), Li et al. (2011), while the spherical droplet was considered by Haller et al. (2002) and Sasaki et al. (2016). Furthermore, the liquid film damping effect on the LDI was numerically studied by Xiong et al. (2011, 2012) and Sasaki et al. (2016), because the real surface in a pipeline is wet with unstable free-surface condition due to multiple droplets impingement. According to the numerical results above, the impact pressure on the wet surface decreased significantly from that on the dry surface because of the liquid film damping effect. Moreover, the fluid-structure interaction problem of LDI erosion was studied numerically by Sasaki et al. (2016). These past studies on numerical simulations replicate the fundamental physics of the droplet impact on the smooth surface observed by visual experiment by Field et al. (1989).

The purpose of this paper is to study the LDI phenomenon on a single groove, as a typical representation of a rough surface. The physical mechanism of the LDI on single groove roughness is numerically studied by the two-phase full Eulerian approach and the results are compared with the experimental observation of the groove erosion by a SEM.

## 2. Numerical method

The physics of the LDI on single groove roughness is a complex two-phase flow phenomenon with deformation at the material interface, followed by the shock wave propagation, which causes difficulty in simulating the LDI phenomenon. In the present work, numerical simulation of a single liquid droplet is carried out utilizing the two-phase full Eulerian approach based on a high-resolution finite volume method. The present work examines the impact of a water droplet impact with the diameter of $D = 30\,\mu\text{m}$ and the velocity of $V = 150\,\text{m/s}$ toward a wall with single groove roughness. Such high velocity droplet impingement is a two-phase flow phenomenon in a steam pipeline of a power plant, where the inertia effect dominates owing to the high Reynolds number.

### 2.1. Governing equation

The numerical simulation of LDI is carried out using a two-dimensional compressible form of Euler equations for two-phase flows, which are basically the same as the former studies of LDI, such as Arai and Koshizuka (2009), Xiong et al. (2011) and Li et al. (2011). It is noted that the two-dimensional assumption is reasonable to consider the mechanism of LDI. The Euler equations (continuity, momentum, and energy conservation equations) can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla\cdot(\rho \mathbf{u} \otimes \mathbf{u}) + \nabla P = 0 \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla\cdot(\mathbf{u}(E + P)) = 0 \tag{3}$$

Here, ρ is the density, $\mathbf{u}$ is the velocity, $P$ is the pressure and $E$ is the total energy given by

$$E = \rho e + \frac{1}{2}\rho \mathbf{u}\cdot\mathbf{u} \tag{4}$$

where $e$ is the specific internal energy. The system is closed by specifying a relationship between the pressure and the energy utilizing the stiffen gas equation as follows:

$$\Gamma P + \Pi_\infty = E - \frac{\rho}{2}\mathbf{u}^2 \tag{5}$$

where $\Gamma = 1/(\gamma - 1)$ and $\Pi_\infty = \gamma P_\infty/(\gamma - 1)$. For perfect gases, γ is the ratio of specific heats and $P_\infty = 0$. For water, γ and $P_\infty$ are determined from Hugoniot data (Saurel and Abgrall, 1999; Haller et al., 2002). It is noted here that the effects of the viscosity and the surface tension are neglected since these effects are small for the high-speed droplet impact with higher Reynolds number and Weber number in reference to the former studies (Haller et al., 2002; Sanada et al., 2011; Xiong et al. 2011). The minor effect of surface tension appears near the meniscus boundary in LDI, but the shock wave formation is not affected by this effect (Haller et al., 2002).

In the two-phase full Eulerian approach used in this work, the interfaces between the two fluid components are specified by a discontinuity in the fluid composition characterized by the material properties Γ and $\Pi_\infty$, which obey the following advection equations (Shyue, 1998; Johnsen and Colonius, 2006),

$$\frac{\partial \Theta}{\partial t} + \mathbf{u}\cdot\nabla\Theta = 0 \tag{6}$$

where $\boldsymbol{\Theta} = [\Gamma\ \Pi_\infty]^{\mathrm{T}}$ is the vector of material properties. To solve the advection equations using the same numerical solver as the Euler equations, the advection equations are converted to the quasi-conservative form utilizing the chain rule as follows:

$$\frac{\partial \Theta}{\partial t} + \nabla\cdot(\mathbf{u}\Theta) = \Theta\nabla\cdot\mathbf{u} \tag{7}$$

### 2.2. Spatial discretization and time-marching

In order to solve the compressible multiphase flow problems in the present studies, Eqs. (1)–(7) are summarized as follows:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial y} = \mathbf{S}(\mathbf{U}) \tag{8}$$

where