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Damping effect on impact pressure from liquid droplet impingement on wet wall

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ABSTRACT

Damping of the impact pressure from liquid droplet impingement (LDI) on a wet wall was studied by numerical simulation and experiment. The numerical simulation was carried out for the impact of an axisymmetric spherical droplet on a wet wall using a compressible form of the Euler equations combined with the stiffened gas equation. The impact pressures on the wall were highly damped by the influence of the liquid film prevailing over the wet wall, and the damping effect was formulated as a function of the liquid-film thickness to droplet diameter. The physical mechanism of the liquid-film damping effect is due to the two-stage compression during LDI and its weakening by the diffraction of the shock wave propagated in the liquid film. In order to understand the liquid-film damping effect obtained from the numerical simulation, experiments on LDI erosion on a wet wall were carried out for various liquid temperatures, which generated a thinner liquid film on the wall at higher temperatures by the viscous effect. The experimental results indicated that the LDI erosion rate increased with rising liquid temperatures, which corresponds to the erosion-rate growth at thinner liquid-film thicknesses. This result is consistent with the liquid-film damping effect obtained from the numerical simulation.

1. Introduction

Pipelines of nuclear/fossil power plants suffer from erosion owing to the impingement of the liquid droplets in a steam flow, and this is one of the crucial topic of interests in the safety management of power plants. Liquid droplet impingement (LDI) erosion is often observed downstream of orifices, elbows, and T junctions of power plant pipelines, where the local flow velocity becomes sufficiently high near the wall and enough liquid droplets are contained in the steam flow. Although there exists some studies on LDI erosion in nuclear/fossil power plants (Sanchez-Caldera et al., 1988; Crocket and Horowitz, 2010; Ikohagi et al., 2010), it is still difficult to predict the LDI erosion rate of actual pipelines in the present stage of research owing to the complexity of the involved physical phenomenon.

In order to understand the mechanism of LDI erosion, the impingement of a single droplet has been studied (Bowden and Brunton, 1961; Heymann, 1969). The impingement of a single droplet on a solid wall is characterized by the liquid droplet deformation in a very short time, which results in the generation of high impact pressure on the wall. As the impact pressure is proportional to the density, sound speed, and impact velocity of the droplet (Heymann, 1969; Rochester and Brunton, 1974), it can easily increase beyond the critical yield stress of the carbon steel in the pipelines of a power plant, where droplet velocity becomes over 100 m/s. Therefore, the major mechanism of LDI erosion in the pipeline is due to the generation of high impact pressure with the impact of liquid droplets on the pipeline wall.

The shadowgraph imaging of a gelatin cylinder allows two-dimensional observation of the transient deformation behavior at the droplet impact on the wall (Field et al., 1985, 1989). The results are illustrated in Fig. 1, which shows the generation of a shock wave at the impact of droplet, which is followed by reflection on the free surface of the droplet and results in the generation of an expansion wave and a cavitation bubble inside the droplet by the focusing. Then, side-jetting is generated over the wall, which is up to 10 times faster than the impact velocity of the droplet (Field et al., 1989).

The wall of a power plant pipeline is considered wet, which is due to the continuous impingement of steam droplets on it. This generates a thin liquid film on the pipe wall. Therefore, the effect of the liquid film has to be taken into consideration when predicting the LDI erosion rate in an actual pipeline, but this has not yet been studied sufficiently in the literature owing to the complex LDI mechanism, which is not easily accessible by an experimental approach (Fujisawa et al., 2013, 2016). Several numerical studies on the impact pressure of LDI have been carried out on dry walls

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Nomenclature

a, b	constants in Eq. (12)
c	sound speed
c_1, c_2	constants in Eqs. (9) and (10)
D	droplet diameter
E	total energy
e	specific internal energy
E_d	erosion depth
P	injection pressure
p	pressure
p_{dry}, p_{wet}	impact pressure on dry and wet wall, respectively
Re	Reynolds number (=VD/ν)
t	time
Q	flow rate
q	local volume flux
u, v	velocities in axial and radial direction, respectively
V	droplet velocity
V_0	velocity at nozzle exit
V_m	non-dimensional erosion rate
We	Weber number (=$\rho DV^2/\sigma$)
x_s	standoff distance
Γ	parameter for stiffen gas equation
δ	thickness of liquid film
η	damping coefficient (=p_{wet}/p_{dry})
κ	non-dimensional liquid-film thickness (=δ/D)
ν	kinematic viscosity of liquid
Π_∞	parameter for stiffen gas equation
ρ	density of liquid
σ	surface tension

(Haller et al., 2002; Arai and Koshizuka, 2009, Li et al., 2011, Sanada et al., 2011), which reproduced the deformation behavior of a liquid droplet on a wall, including the generation of the shock wave followed by an expansion wave and the focusing, which resulted in the formation of a low pressure region in the liquid droplet and the cavitation inception. On the other hand, only a few numerical simulations have been reported on LDI on a wet wall (Xiong et al., 2011; Sasaki et al., 2016), which is the case of practical interest. The numerical simulation of the high-speed droplet impact on a wet wall indicated that the impact pressure decreased in the presence of a liquid film of several micrometers over the solid surface. It is known that this reduction in impact pressure is due to the damping effect of the liquid film. However, these results seem to be deviated owing to the assumptions made in the numerical simulations, such as 2-D simulation for a droplet of cylindrical shape by Xiong et al. (2011) and 3-D simulation for a droplet of spherical shape with material effect by Sasaki et al. (2016). Therefore, there is a need for further numerical studies on the impact-pressure damping effect on a wet wall to understand the LDI mechanism under this condition. Furthermore, there is a lack of direct experimental evidence on the liquid film damping effect because of the experimental difficulty in measuring the thin liquid film on the wall and the impact pressure acting on the pipe wall.

The purpose of this work is to study the liquid-film damping effect on LDI erosion by both numerical simulation and experiment. The liquid-film damping effect on the impact pressure was studied under the assumption of spherical droplet impact and rigid wall. Furthermore, the liquid-film damping effect was experimentally studied through variation in liquid temperature, which allows the change in the liquid-film thickness prevailing on the wall.

2. Numerical simulation

The present work examines the impact of a water droplet with diameter D = 35 μm and velocity V = 140 m/s on a wall with liquid film, where the inertia effect dominates owing to the high Reynolds number. In addition, we focus on the early stage behavior of LDI on the liquid film, where inviscid mechanisms dominate the behavior. For each fluid component in compressible two-phase flows, the governing Euler equations can be written as follows, under the assumption of rotational symmetry:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial r}(\rho v)+\frac{\partial}{\partial z}(\rho u)=-\frac{\rho v}{r} \tag{1}$$

$$\frac{\partial}{\partial t}(\rho v)+\frac{\partial}{\partial z}(\rho v u)+\frac{\partial}{\partial r}(\rho u^2)+\frac{\partial}{\partial r}p=-\frac{\rho v^2}{r} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial r}(\rho v u)+\frac{\partial}{\partial z}(\rho u^2)+\frac{\partial}{\partial z}p=-\frac{\rho v u}{r} \tag{3}$$

$$\frac{\partial E}{\partial t}+\frac{\partial}{\partial r}(E+p)v+\frac{\partial}{\partial z}(E+p)u=-\frac{(E+p)v}{r} \tag{4}$$

Here, u and v are the velocities in axial and radial direction, respectively, ρ is the density, p is the pressure, and E is the total energy given by

$$E=\rho e+\frac{\rho}{2}(u^2+v^2) \tag{5}$$

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

$$\Gamma p+\Pi_\infty=E-\frac{\rho}{2}(u^2+v^2) \tag{6}$$

where Γ = 1/(γ-1) and Π_∞ = γP_∞/(γ-1). γ and P_∞ are the fitting parameters for the stiffened gas equation. It is noted here that the effect of the viscosity and the surface tension are neglected since these are considered small for the high-speed LDI in high Reynolds number and Weber number. This is the same situation as the former numerical studies of LDI (Haller et al., 2002; Sanada et al., 2011; Xiong et al., 2011. Fujisawa et al., 2018). An interface capturing approach (Fujisawa et al., 2018) is utilized in the simulations.

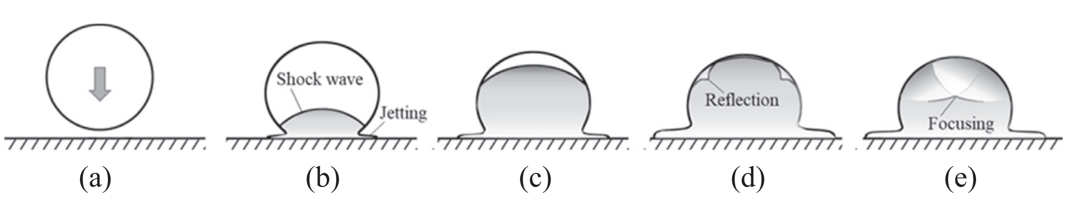

Fig. 1. Time-series variation of droplet impact phenomenon on solid surface (a) Droplet attack, (b), (c) Shock-wave formation, (d) Expansion wave formation (e) Focusing and cavitation bubble formation.