Numerical analysis of liquid droplet impingement on rough material surface with water pool

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Abstract. Liquid droplet impingement erosion occurs at the elbows in steam pipes where droplets impinge at high speed. In the actual pipe wall which numerous droplets always impinge, it is predicted that both a liquid film exists on a pipe wall surface and, on the other hand, this surface is also eroded by repeated droplet impingement. Therefore, the liquid film and roughness on the material surfaces are considered to exist mixed on the actual impinged point of droplets. In this study, by using an in-house fluid/material two-way coupled numerical method that considers reflection and transmission on the fluid/material interface, the numerical analysis of the phenomenon of liquid droplet impingement on a pitted surface with a water pool is conducted. From the analysis results, the impinged pressure at the moment of impingement is alleviated by a water pool. However, as the cavitation bubbles are generated in the bottom and top of the droplet and then the cavitation bubble of the bottom side collapses, the collapse pressure which greatly exceeds the pressure of the droplet impingement occurs, and the equivalent stress also increases greatly there. Therefore, this analysis result may indicate one reason why the erosion progresses deeply at the pit part in an actual pipe wall thinning.

1. Introduction
Liquid droplet impingement erosion occurs at the area where droplets impinge on fluid machinery at high speed, such as the last stage of blades in steam turbines and the elbows in steam pipes. In particular, the pinholes in piping generated by a pipe wall thinning in aging nuclear power plants can cause serious accidents such as leakage of radioactive materials [1], therefore, it is important to understand the influence of high-speed droplet impingement on the pipe wall thinning rate. In an actual pipe wall, due to droplet impingement, it is predicted that the liquid film exists on the material surface. Regarding the influence of liquid film for droplet impingement, it has been thought that the impingement pressure is damped and the erosion of materials is suppressed. In existing studies, Shi et al. [2] reported that the droplet impingement was damped by an existence of a liquid film, Fujisawa, N et al. [3] conducted an experimental study on the effect of a liquid film on material under droplet impingement and proposed an equation of the erosion rate considering the effect of the liquid film, Fujisawa, K et al. [4] conducted an evaluation of the effect of a liquid film on material in the droplet impingement experimentally and numerically. We have also numerically showed that the pressure caused by a droplet impingement is damped by the liquid film [5]. On the other hand, the pipe wall surfaces are not completely smooth, as the wall surfaces are eroded by repeated droplet impingement and these material surfaces also have initial roughness from processing during manufacture. Therefore, it is considered that droplets impinge on the material surface on which wetness and roughness simultaneously exist. However, our previous numerical analysis [5] was assumed that the material surface was an ideal surface which was perfectly smooth, and the influence of roughness on a material surface was not considered.
Actually, it has also been reported that an elbow surface with a pinhole has numerous pits and that the surface is considerably rough as shown Figure 1. In addition, since the erosion is progressing to a relatively deep level in these pits of roughness, the liquid film by droplet impingement flows to these pits and the water may accumulate in the depressed pits. From these facts, in an environment where this erosion actually occurs, it is considered that there is a water pool inside a roughness on the material surface. Therefore, it is necessary to investigate the droplet impingement on a rough material surface with a water pool. Furthermore, in order for the erosion to progress deeply at the pit bottom, it is assumed that not the droplet impingement but the cavitation bubbles generated by a droplet impingement[6][7] affect this erosion of the pit bottom. In this study, by using an in-house fluid/material two-way coupled numerical method that considers reflection and transmission on the fluid/material interface, the numerical analysis of the phenomenon of a liquid droplet impingement on a pitted surface with a water pool is conducted. The influence of the water depth inside a pit and droplet impinging velocity on the droplet behavior is analyzed and the possibility of the liquid droplet impingement erosion is discussed. Especially, the influence of cavitation bubbles which occur inside the droplet during the droplet impingement is noted.

Figure 1. Rough surface of elbow by droplet impingement in nuclear power plant [1].

2. Numerical Method

2.1. Governing Equation in Fluid
In this study, the locally homogeneous model of a compressible gas-liquid two-phase medium with phase changes [8], [9], [10] is used as the interface capturing method in a droplet interface. The governing equations in fluid are the continuity, the momentum equations, the total energy conservation equation of a gas-liquid mixture phase, and the continuity equation of the gas phase. The governing equation system is closed by satisfying the follow two equations, that are the equation of state of a homogeneous medium and the total energy equation of a two-phase medium. In addition, in order to consider the cavitation bubble which occurs inside the droplet during a high-speed droplet impingement, the phase change model of which the phase equilibrium theory of a flat gas-liquid interface [11] is extended to a homogeneous gas-liquid two-phase medium [12] is used. The saturated vapor pressure of water, \( p_v \), is calculated by the empirical formula given by Sugawara [13].

2.2. Governing Equation in Material
For the simulation of stress wave propagation in a material, the governing equations comprising the equation of motion and the time-differential constitutive equations of a homogeneous isotropic elastic medium are solved simultaneously [14]. The material deformation and density change are neglected.
2.3. Numerical Scheme of Analyzing Method

The cell-centered finite volume formulation is used to discretize the governing equations of both the fluid and the material. The convective term is estimated as an AUSM-type scheme with interpolation using the 3rd-order MUSCL-TVD method with a minmod limiter. The 4th-order Runge-Kutta method is used for the time integration. The algorithm of the two-way coupled method at the fluid/material interface [15] is applied as follows: The fluid surface pressure and normal stress in the vertical direction on the material surface are obtained by considering the reflection and transmission of pressure and stress waves with acoustic impedance. Non-slip conditions are adopted on the fluid/material surface, where the vertical velocity has the values which are obtained by considering the reflection and transmission, and the tangential velocity of the fluid has the same velocity of the material which is calculated by the material analysis.

3. Results and Discussion

3.1. Calculation Condition

The calculation condition and pit shape are shown as Figure 2. In this study, it is assumed that the droplet impinges on the center of a pit and water pool. The range of the impingement velocity $V$ is a few tens to a few hundreds m/s and the droplet diameter is $d = 100 \, \mu m$. The initial temperature and pressure of the water droplet in vapor are $T = 293.15 \, K$ and $p = 0.1 \, MPa$, respectively. In addition, this droplet includes the mass fraction of the gas phase $Y = 1.0 \times 10^{-9}$.

The material is assumed to be steel and the initial stress of the material is a compressive stress of 0.1 MPa. The material properties for steel are density $\rho_s = 7800 \, kg/m^3$, Young’s modulus $E = 200 \, GPa$, and Poisson’s ratio $\nu = 0.3$. In the boundary of calculation area, the temperature is fixed at 293.15 K. In this calculation, because the displacement of the material is very small in the occasion of the micro scale single droplet impingement, the whole of the material which includes its surface is calculated with a fixed mesh system although the displacement velocity is taken into account. In detail of the pit shape, this pit is sphere and the maximum depth and radius are $D_{Pit} = 0.2d$ and $R_{Pit} = 0.4d$, respectively.

![Figure 2. Calculation condition with pit shape.](image)
3.2. Threshold for Influence Evaluation of Materials

In this study, the threshold flow velocity in experiments which the erosion rate becomes negligible small [16] is used for the evaluation of the influence of the droplet impingement and collapse of cavitation bubbles on materials in a calculation. The maximum equivalent stress in each place calculated by our numerical method from this threshold flow velocity is used as the influence threshold of the material. Here, in order to assume the droplet impingement mainly to stainless steel, in the case of stainless steel of SUS304, this threshold flow velocity is 120 m/s [16]. By using our numerical analysis method, when the droplet impingement velocity is \( V = 120 \text{ m/s} \) the maximum equivalent stress in whole computational region becomes \((\sigma_{eq})_{max} = 165 \text{ MPa}\) (Figure 3). Therefore, this value, 165 MPa, is used for the threshold value of equivalent stress when a material is affected by the stress.

![Figure 3. Determination of threshold value of equivalent stress for evaluation of material.](image)

3.3. Droplet Impingement on Pit Surface with Water Pool

In order to analyze the influence of the depth of water pool accumulating in the pit, the calculation of which the droplet impingement velocity is a constant \( V = 200 \text{ m/s} \) and the maximum depth of water pools is changed with 0.1\( d \), 0.15\( d \), 0.2\( d \) (Figure 4) is conducted.

![Figure 4. Each depth of water pool.](image)

Figures 5, 7 and 9 show the distributions of the pressure and void fraction in the fluid side and the equivalent stress in the material side at aspect of \( z = 0 \), where the gas-liquid interface of the droplet is drawn by the black solid line which is assumed at void fraction \( \alpha = 0.5 \) and the time \( t = 0 \) indicates the moment when the bottom of a droplet just contacts the water surface. In all cases of water depth, when the droplet impinges on the pool surface, the pressure waves propagate inside the water pool and droplet. Since the droplet interface continuously impinges on the water surface, the contact edge is made at the touching point of droplet with water pool and the contact edge moves on the outside. In the case of water depth of 0.1\( d \) and 0.15\( d \), since the contact edge concentrates on the pit region of the material surface, the pressure and equivalent stress exceeding the impingement pressure occur (Figures 5(a) and 7(a)).
After occurring this higher pressure, these pressure waves propagate inside a droplet as compression waves and then these compression waves change to the expansion waves due to reflection at the gas-liquid interface with mismatch of acoustic impedance. The interference of expansion waves gets a local pressure down in upper and down region inside the droplet, and the two cavitation bubbles occur at these low pressure region by evaporation (Figures 5(b) and 7(b)). The lower cavitation bubble collapses by the compression waves and the highest pressure and equivalent stress occur at the bottom of the droplet and pit, therefore, these results show that the erosion may progress further at the bottom of a pit (Figures 5(c) and 7(c)). Figures 6 and 8 show the time variation of the maximum pressure in fluid side \( p_{\text{max}} \) and the maximum equivalent stress in the material side \( (\sigma_{\text{eq}})_{\text{max}} \). These figures show that in the early stages of the droplet impingement, the impingement pressure is alleviated by the water pool and then the pressure sharply rises by the concentration of the contact edge on the pit surface. As further the impingement progress, since the cavitation bubble occurs and collapses, the highest pressure through this impingement whole occurs. In particular, in the case of \( 0.1d \), since the pressure concentration by the contact edge is
stronger, as a result, the collapse pressure by the cavitation bubble at the bottom of the droplet is much higher than that of $0.15d$.

![Diagram](image1)

(a) $t = 0.062 \mu s$  (b) $t = 0.160 \mu s$  (c) $t = 0.176 \mu s$

**Figure 7.** Time variation of pressure and void fraction in fluid and equivalent stress in material ($V = 200$ m/s, $d = 100 \mu m$, depth of water pool = $0.15d$).

![Diagram](image2)

**Figure 8.** Time variation of $p_{\text{max}}$ in fluid side and $(\sigma_{\text{eq}})_{\text{max}}$ in material side ($V = 200$ m/s, $d = 100 \mu m$, depth of water pool = $0.15d$).

On the other hand, in the case of $0.2d$ in Figures 9 and 10 where the pit is filled by water, since the concentration of pressure on the pit region of the material surface does not occur between the contact edge and the pit surface, the occurrence and collapse of cavitation bubbles do not occur either (Figure 9). Figure 10 also shows that the pressure peak is not seen except the pressure rising at the initial of the droplet impingement. Therefore, if the state is that the pit surface is not completely covered by water and the water accumulates less than a half depth of a pit, it is considered that the erosion is accelerated locally at the bottom of pits due to the collapse of cavitation bubbles.
Figure 9. Time variation of pressure and void fraction in fluid and equivalent stress in material ($V = 200$ m/s, $d = 100$ µm, depth of water pool = 0.2$d$).

Figure 10. Time variation of $p_{\text{max}}$ in fluid side and $(\sigma_{\text{eq}})_{\text{max}}$ in material side ($V = 200$ m/s, $d = 100$ µm, depth of water pool = 0.2$d$).

Next, in order to analyze the influence of the droplet impingement velocity, the calculation of which the depth of water pools is a constant 0.1$d$, and the impingement velocity $V$ is changed with 80, 100, 200 m/s is conducted. Figures 11 and 13 show the distributions of the pressure and void fraction in the fluid side and the equivalent stress in the material side of the each case of $V = 100$ and 80 m/s, respectively. Figures 12 and 14 show the time variation of the maximum pressure in the fluid side $p_{\text{max}}$ and the maximum equivalent stress in the material side $(\sigma_{\text{eq}})_{\text{max}}$ of the each case of $V = 100$ and 80 m/s, respectively. The result of $V = 200$ m/s is the same result of the previous section, in this case, both of the droplet impingement and the collapse of the cavitation bubble have an effect on the material because the maximum equivalent stress exceeds the threshold value of 165 MPa in both the droplet impingement and bubble collapse. However, in the cases of 80 and 100 m/s, since the impingement pressure becomes small with decreasing the impingement velocity, the maximum equivalent stress becomes also under the threshold value, so that the droplet impingement does not have an effect on the material. In contrast, since the collapse pressure of the cavitation bubble is much larger than that of the droplet impingement,
the equivalent stress also exceeds the threshold value, in this case, it can be considered that the collapse of a cavitation bubble has an effect on the material. By the way, when the droplet impinges on a dry and flat surface at velocities of 80 and 100 m/s, in a similar way, it has been confirmed that the pressure due to a droplet impingement is below the threshold value and the cavitation bubble at the droplet downside does not occur either [15]. Therefore, even in the range where the impingement velocity which is assumed to make erosion hard to progress is somewhat slow, if the material surface has pits and the water accumulating in the pits, the erosion in the bottom of pits may be accelerated due to the collapse of cavitation bubbles.

From the above results, in this study, it is shown that if a pit exists on the material surface and the water accumulates in this pit, the liquid film which usually has a decrement effect of the impingement pressure makes the erosion of a material accelerated by the collapse pressure of cavitation bubbles. Especially, in the erosion mark by the liquid droplet impingement, since the collapse pressure of cavitation bubbles strongly acts on the bottom center of pits, this is considered to be the mechanism of which the material surface is getting more and more eroded with keeping the pit shape.

Figure 11. Time variation of pressure and void fraction in fluid and equivalent stress in material ($V = 100 \text{ m/s}, d = 100 \mu\text{m}, \text{depth of water pool} = 0.1d$).

Figure 12. Time variation of $p_{\text{max}}$ in fluid side and $(\sigma_{\text{eq}})_{\text{max}}$ in material side ($V = 100 \text{ m/s}, d = 100 \mu\text{m}, \text{depth of water pool} = 0.1d$).
4. Conclusions
In this study, the numerical analysis in which a single droplet vertically impinges on the rough material surface with water pool is conducted by means of the fluid/material coupled numerical analysis method which considers reflection and transmission of waves on the boundary interface. The results are summarized as follows:

In the case where the pit is filled with water, the impact of a liquid droplet impingement is damped by the water pool. However, it is shown that there is the possibility of which the impact by droplet impingement becomes conversely strong by the occurrence and collapse of a cavitation bubble during a droplet impingement if the water accumulates on the pit existing on a material surface about a half. In addition, since this bubble collapse occurs in the pit bottom, the pit bottom receives the higher impact pressure and may be damaged locally. This result may indicate one reason why the mechanism of erosion progressing with keeping the shape of a pit despite droplets evenly impinging.
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