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Method for Thinning Shape Evaluation of Elbow due to LDI and Representative Thinning Shape for Seismic Evaluation of Eroded Elbow

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ABSTRACT

For more realistic seismic safety evaluation of elbow with local thinning shape due to liquid droplet impingement erosion (LDI), a determination method of the thinning shape of the elbow due to LDI was developed, and a representative thinning shape for seismic evaluation of eroded elbows was proposed in this study. For the mechanistically-based determination of the thinning shape due to LDI, calculations of the droplet behavior and the thinning rate of the elbow were conducted. In addition, with this approach, the thinning shapes in various flow and piping size conditions were evaluated, and the enveloping thinning shape of those thinning shapes with a safety factor is considered as a representative thinning shape for seismic evaluation of eroded elbows.

KEYWORDS

Liquid droplet impingement erosion, Seismic evaluation, Thinning shape

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1. Introduction

Liquid droplet impingement erosion (LDI, see Fig.1) is defined as the erosion caused by the collision of high-speed droplets in a steam flow. In a power plant, pipe wall thinning by LDI is observed in steam piping systems such as the vent line. LDI is usually observed very locally and is difficult to detect.

Recently, for seismic safety of piping system with wall thinning, uniform thinning over the full pipe circumference was assumed for the safety analysis [1]. Generally, the piping strength for the seismic evaluation is reduced when the piping wall thickness becomes thinner and wider. For this reason, the assumption of overall uniform thinning is thought of as giving a conservative evaluation result. However, at an elbow section, LDI is often observed at the elbow extrados because of its mechanism, and the local thinning shape is generated. Because of the difference of the thinning shape between the overall uniform thinning assumption and actual local thinning, the seismic evaluation of eroded elbows with uniform thinning gave a different result from that with an actual thinning shape [2]. Though the influences of the local thinning of the elbow to the fatigue characteristics are investigated, the thinning shape was not decided mechanistically [3]. For more realistic seismic evaluation of the eroded elbow due to LDI, it is necessary to determine more realistic thinning shape of the elbow with the LDI mechanism.

In this paper, the determination method of the thinning shape of the elbow due to LDI with its mechanism, including calculations of the droplet behavior and the thinning rate, has been developed. In addition, a representative thinning shape, which covers the thinning shape due to LDI in an actual plant, is proposed for the seismic safety evaluation.

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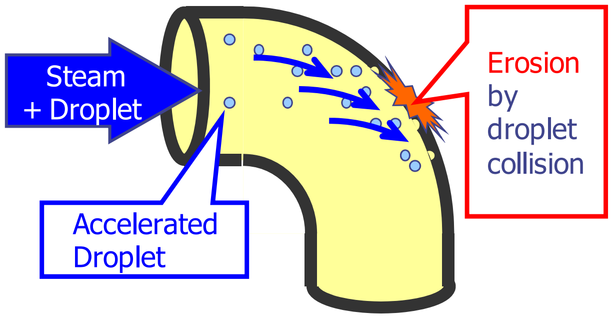


Fig.1 Schematics of Liquid Droplet Impingement Erosion in Piping System

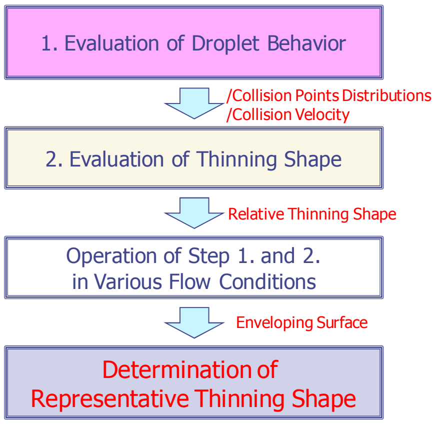


Fig.2 Flowchart of LDI Thinning Shape Determination

2. Development of Determination Method

2.1. Evaluation of Droplet Behavior

The evaluation flowchart of LDI thinning shape determination for the seismic tests (representative thinning shape) is shown in Fig.2. At first, the droplet behavior from the elbow inlet to the collision point is calculated to evaluate the distributions of the collision point and collision velocity.

Figure 3 shows the concept of the droplet behavior calculations. Steam flow velocity u_g distributions in the elbow are assumed as uniform in the flow direction and no secondary flow.

$$\left.\begin{aligned} u_{g,\theta} &= u_{in} \\ u_{g,r} &= u_{g,\phi} = 0 \end{aligned}\right\},$$

u_θ: Flow Direction Velocity, u_r: Radial Direction Velocity,
u_ϕ: Circumferential Direction Velocity

(1)

For more accurate droplet behavior calculation, a 3-dimensional flow calculation is applied to obtain the velocity distributions in the elbow. This procedure with 3D calculations can be estimated actual data reasonably as mentioned after. However, in this study, as a lot of parametric study is necessary, it is not realistic to apply 3D calculations.

Droplets are assumed uniform distributions at the elbow inlet, and section area S is assigned. Then, the behavior of each droplet is calculated until it collides with the elbow wall (or it passes through the elbow). The droplet is transferred by a drag force from steam flow, and displacement dx for a certain time step dt is calculated as follows.

$$dx = 0.5\rho_l(u_l\text{-}u_g)|\, u_l\text{-}u_g\,| C_d\, A\, dt,$$

A: Projected Area of Droplet ($=\pi d^2/4$), C_d: Drag Coefficient of Droplet

(2)

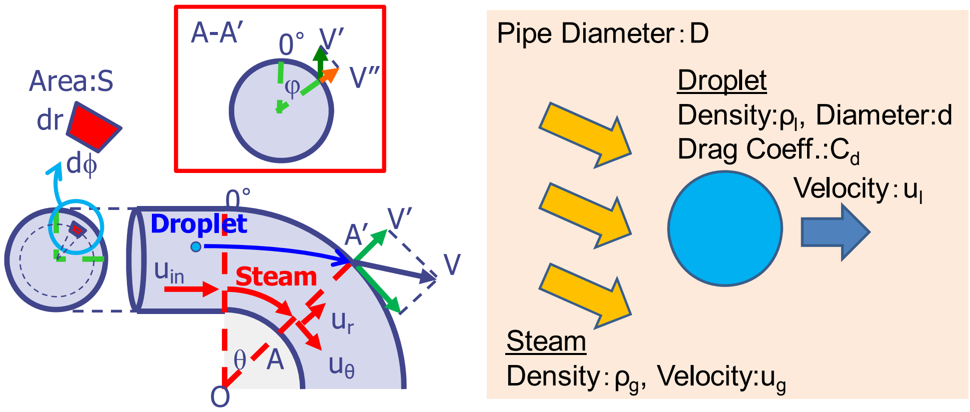


Fig.3 Concept of Droplet Behavior Calculations

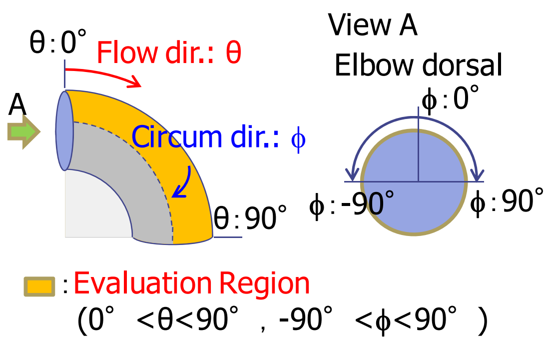


Fig.4 Evaluation Region of LDI Thinning Shape

A droplet at position x_n in time t moves to a new position $x_n+1=x_n+dx$ in $t+dt$ with flow conditions at x_n. Then, the flow conditions are updated to the values at x_{n+1}, and new displacement dx_{n+1} is calculated. This procedure is conducted in *x*, *y*, *z* directions and repeated until the droplet collides with the elbow or passes through the elbow section. Figure 4 shows evaluation region of the droplet collision and LDI thinning shape. The evaluation region is along the elbow extrados, and is divided into 30 sections both in the flow direction (θ) and the circumferential direction (ϕ).

When the droplet collides with elbow wall, the position (θ, ϕ) and the collision velocity are recorded. Applying this operation to all droplets, distributions of the collision point and the average collision velocity are obtained.

In this study, the droplet behavior calculation and thinning shape evaluation has been conducted for various flow and geometry conditions to evaluate a representative thinning shape. The parameters of the calculations and the reason why the parameter range was chosen are as follows.

1. **Steam velocity, *u***: 100, 200, 400 m/s
   Reason: Lower limit velocity of LDI has been reported around 100m/s [4]. Steam velocity in the piping is assumed below sonic speed (about 450m/s in wet steam).
2. **Pressure, *p***: 0.005, 0.01, 0.1, 1.0, 7.0 MPa
   Reason: Range of pressure in main steam piping to condenser pressure.
3. **Droplet Diameter, *d***: 1.0, 2.0, 5.0, 10, 20, 50 μm
   Reason: From droplet diameter measurement tests in CRIEPI [5], the average diameter was within 1-20μm and 99% of droplet diameters were bound by twice the average.
4. **Pipe Diameter, *D***: 50, 100, 150, 300, 400 mm
   Reason: Typical of the wet steam piping diameter in actual power plants.

Distributions of the collision point and the average collision velocity are evaluated in all combinations of these parameters (total 450 conditions).

2.2. Evaluation of Thinning Shape

After the droplet behavior calculations with the method described in 2.1, the thinning shape on the elbow was estimated with LDI thinning rate model. The Sanchez model [5] was used in this study. The Sanchez model equation is expressed as follows.

$$T.R. = \frac{C_0 \rho_l m_{tot} \beta u_l^{\,4} F_e F_h}{(MAT)^2 A_C},$$

T.R.: Thinning Rate, C_0: Coefficient(=1.1e-6 [6]), m_{tot}: Mass Flow Rate, β: Wetness
u_l: Collision Velocity, F_e: Entrainment Factor, F_h: Hitting Factor
MAT: Material Factor (Strength of Oxide Film on Material Surface), A_C: Collision Area

(3)

Sanchez model is proportional to the 4th power of the collision velocity. This tendency was same as observed in Rochester's research [7].

For the validation of the basic parts of the droplet behavior evaluations (all concepts except velocity distributions (eq.(1))) and LDI thinning rate model, the comparison between actual LDI data and thinning shape evaluation with 3-dimensional calculation was conducted. Figure 5 shows a thinning shape of 1st elbow of an orifice downstream in a vent line of an actual power plant, and Fig. 6 shows the velocity distributions around this elbow and evaluated thinning shape of the elbow with 3-dimensional flow calculation. The thinning rate is normalized with maximum thinning rate of each data. Because the wall thickness (absolute value of the erosion rate) will be given as the parameter in the seismic tests, it is necessary to evaluate the normalized (relative) thinning shape in this study. Therefore, a relative thinning rate was compared.

From these figures, a jet flow was observed because of the orifice and the flow structure becomes very complex. However, both thinning shape were distributed almost same region ((θ, ϕ) = (30~60 deg., -40~40 deg.)). And also, Fig. 7 shows the comparison of the thinning shape distributions of sections A and B in Fig.5. Sections A and B were the sections which maximum thinning rate is observed in actual data. It is shown that the evaluated thinning shape with 3-dimensional calculation agrees well with actual data qualitatively, and we have confirmed the basic parts of the evaluation method.

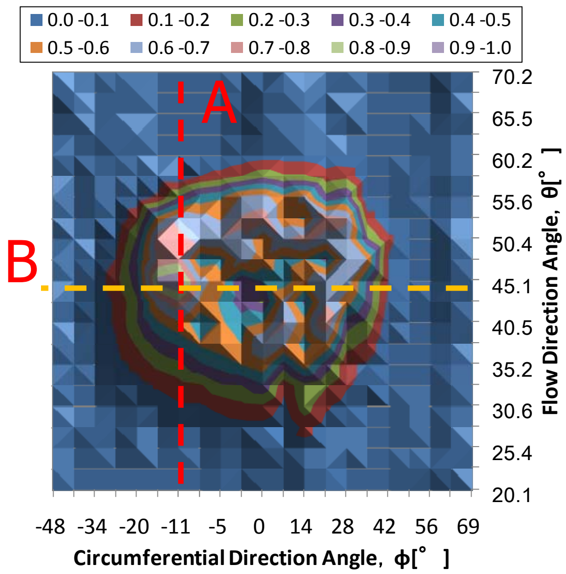
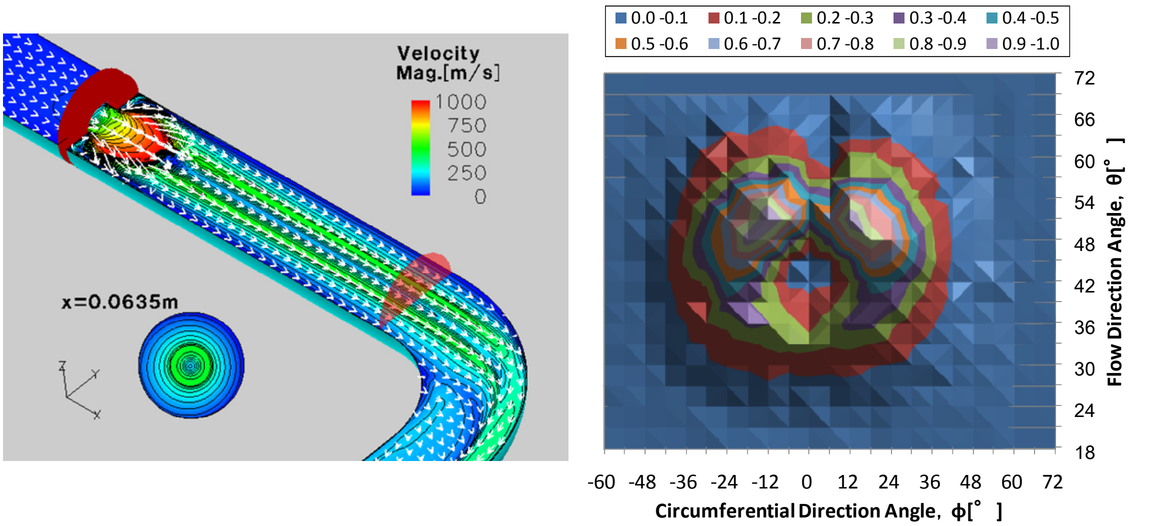
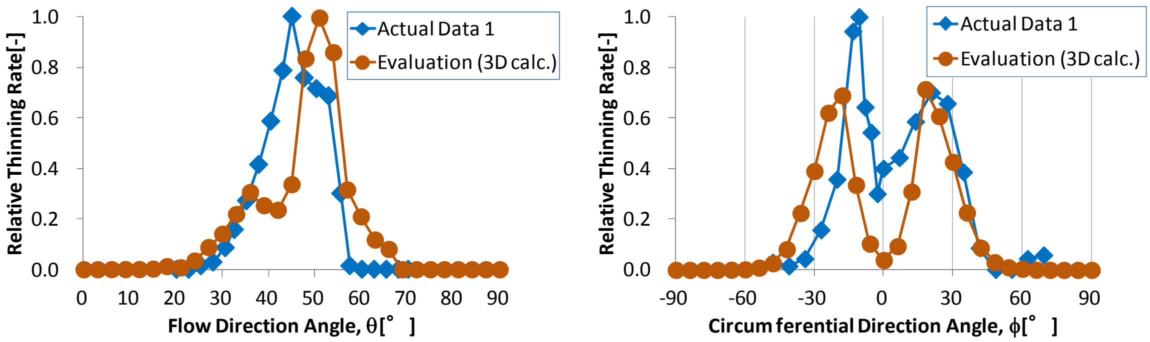


Fig.5 Relative Thinning Shape at Elbow on Actual Plant
(1st Elbow of Orifice Downstream in Vent Line, Case 1)



(a) Velocity Distribution with 3D Flow Calculation **(b) Thinning Shape**

Fig.6 Evaluated Thinning Shape at Elbow obtained from 3D Calculation Method



(a) Flow Direction (Line A at Fig.5) **(b) Circumferential Direction (Line B at Fig.5)**

Fig.7 Comparison of Thinning Rate Profile

2.3. Determination of Representative Thinning Shape

Figure 8 shows an example of the estimated thinning shape on the extrados side of the elbow. Thinning rate is normalized with maximum thinning rate. In this condition, the erosion shape was distributed concentrically and the maximum erosion point was around (θ, ϕ)=(0deg., 60deg.).

This evaluation procedure of the estimation of the relative thinning shape was repeated for all cases (450 cases) to evaluate the representative thinning shape. Figure 9 shows the evaluation image of the representative thinning shape. As we thought the representative thinning shape needs to be encompassed all evaluated thinning shapes, the thinning rate of an enveloping shape $T.R._{env}(\theta, \phi)$ was evaluated as follows.

$$
T.R._{env}(\theta,\phi) = \max\begin{pmatrix} T.R.(u_1, p_1, d_1, D_1)(\theta,\phi), \\ \dots \\ T.R.(u_i, p_j, d_k, D_l)(\theta,\phi), \\ T.R.(u_i, p_j, d_k, D_{l+1})(\theta,\phi), \\ \dots \\ T.R.(u_{i\max}, p_{j\max}, d_{k\max}, D_{l\max})(\theta,\phi) \end{pmatrix}, \tag{4}
$$

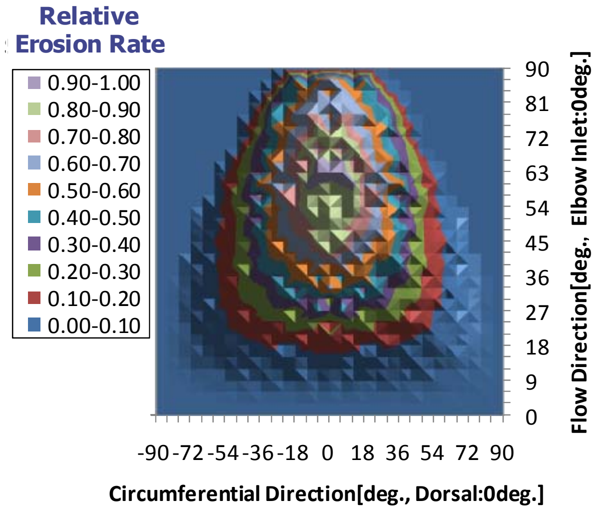


Fig.8 Example of Estimated Thinning Shape
(*p*:0.1MPa, *u*:400m/s, *d*:20mm, *D*:150mm)

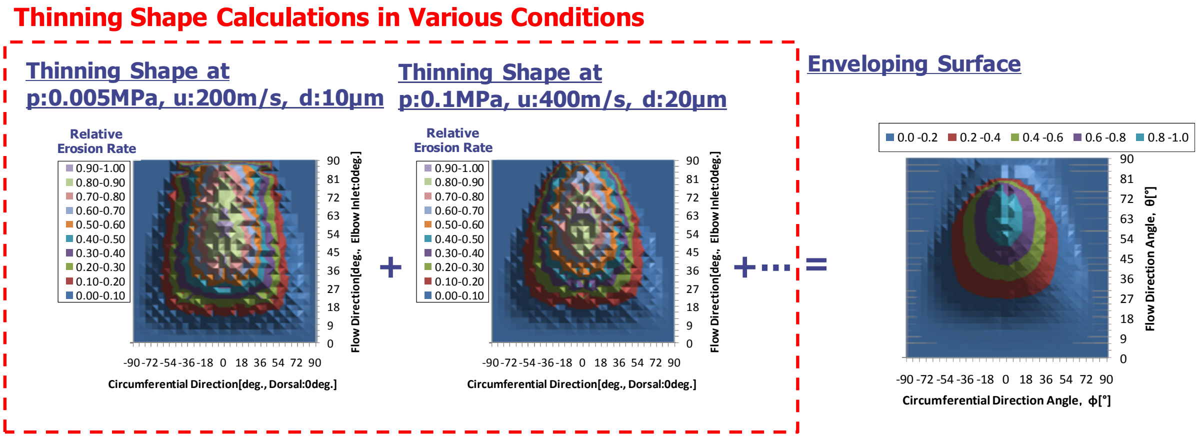


Fig.9 Evaluation of Enveloping Thinning Shape

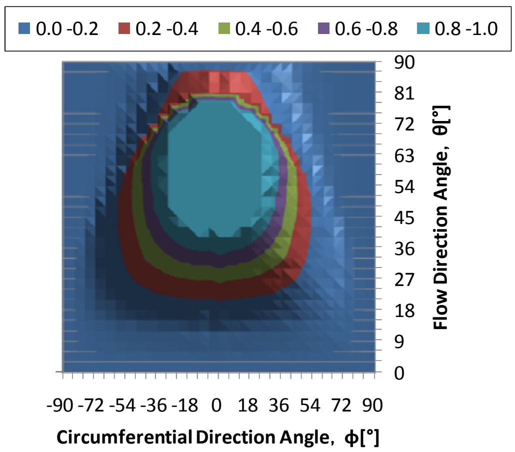


Fig.10 Representative Thinning Shape
(Enveloping Thinning Shape with Factor 2)

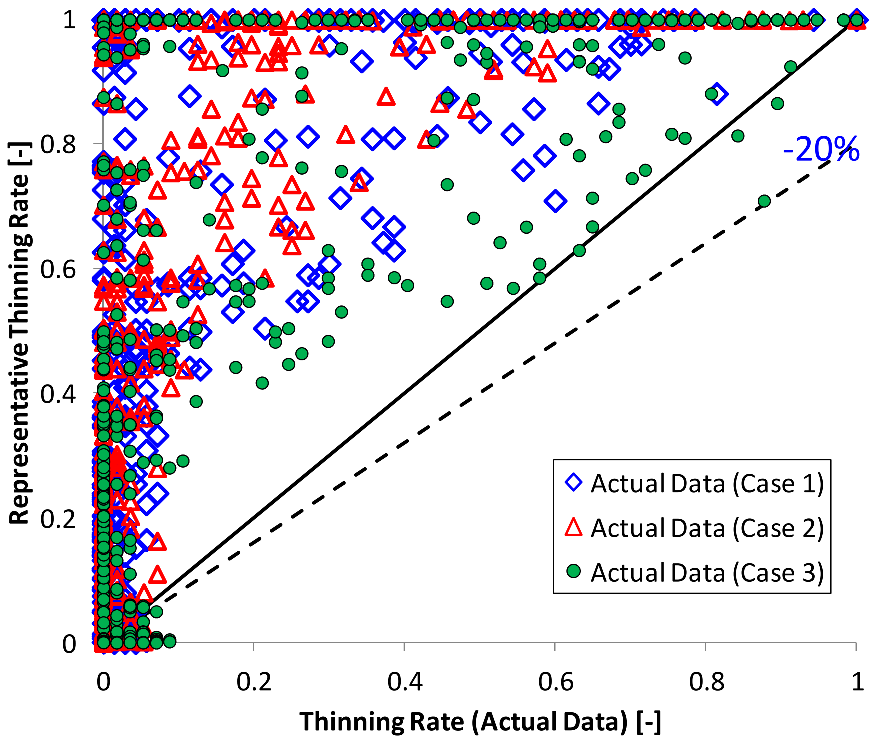


Fig.11 Representative Thinning Rate vs. Thinning Rate of Actual LDI Cases (3 Cases, 1st Elbow of Orifice Downstream in Vent Line)

With this procedure, the enveloping surface was obtained. However, this enveloping shape is evaluated assuming uniform and no secondary flow as described above. In actual cases, LDI is sometimes caused by non-uniform inlet flow condition, like LDI at a valve or downstream of an orifice (see Fig.6). Therefore, a factor 2 was applied to the relative thinning shape of the enveloping surface and we adopt this thinning shape as the representative shape (Fig.10).

The representative thinning shape (enveloping surface with the safety factor 2 applied) for seismic tests was then compared with actual LDI cases. Figure 11 shows the comparisons of the section shape of the thinning rate with the actual data. Cases 1-3 are actual LDI cases of 1st elbow of an orifice downstream in different vent lines, which are considered as the jet flows collide.

From the figure, it was observed that the representative thinning shape bounds almost actual data conservatively (94.6% of all actual data, 99.8% of actual data with T.R.>0.1). As mentioned before, the piping strength for the seismic evaluation becomes smaller when the piping wall thickness is thinner and wider. Therefore, it was thought that the representative thinning shape gave a conservative result of the seismic evaluations. Although some non-conservative points were observed around the small thinning rate region (T.R.<0.1) and T.R.~0.8 (3 points only), it was considered that small thinning rate region and a few points under-estimation of thinning rate have little effect to non-conservativeness of seismic evaluation.

As a result of the comparison, it is clarified that the representative thinning shape estimated with non-secondary uniform flow assumption can encompasses the actual data almost conservatively, and the representative thinning shape is thought to be applicable to the seismic evaluation for the thinned elbow.

3. Conclusion

For more realistic seismic safety evaluation, a determination method of LDI thinning shape at the elbow in line with the LDI mechanism has been developed. The droplet behavior and thinning shape calculation have been conducted under various flow and geometry conditions with an assumed velocity distribution in the elbow. The enveloping shape with safety factor 2 on relative thinning rate was considered as the representative thinning shape. As the representative thinning shape bounded actual LDI thinning shapes conservatively, it was thought that the representative thinning shape was applicable to the seismic evaluation for the thinned elbow due to LDI.

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