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Investigation on droplet impingement erosion during steam generator tube failure accident

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ABSTRACT

Droplet impingement erosion is one of the reasons causing the secondary heat transfer tube damage in case of the heat transfer tube failure in the steam generator of sodium-cooled fast reactor. This paper has been dedicated to investigate the impingement phenomena, pressure load and the damage rate by impingement. Single droplet impingement on the rigid wall was first simulated with MPS-AS (moving particle semi-implicit method for all speeds) method for water and sodium. The shockwave propagation during the impingement has been well captured. The pressure load by water impingement can be characterized with Heymann's correlation (1968). A correlation for pressure load by sodium impingement is proposed based on the water hammer theory. The new correlation shows to be consistent with the simulation result. For prediction of erosion rate by sodium droplet impingement, Heymann's empirical correlations (1979) were extended by including the effects of liquid properties, i.e. density, sound speed and viscosity. The extended correlations show similar prediction accuracy to the original ones.

1. Introduction

In the steam generator (SG) of the sodium-cooled fast reactor the heat transfer tubes is the boundary separating the high-pressure water and the low-pressure liquid sodium. The water flows through the tubes, while the liquid sodium in the shell side. In case of a break on the tube the water leaks into the shell side and reacts violently with the liquid sodium. Depending on the break size the sodium–water reaction can result in a transient characterized by the high-temperature high-speed flame propagation. In such a situation, besides the thermal impact and the corrosive reaction products, the heat transfer tubes and structures in the neighborhood also suffer from the high-speed impingement by the droplets entrained by the expanding flame. These severe conditions can cause the further failure of neighboring tubes and structures and deteriorate the consequence of accident. To optimize the SG design and provide the effective countermeasure against accident, the wastage rate of neighboring tubes caused by the above mechanisms demands to be predicted. In the present paper the authors investigate the high-speed droplet impingement phenomena and the wastage rate resulted from the droplet impingement erosion.

The droplets of three fluids are expected to result in the wastage of neighboring tubes in case of the SG heat transfer tube failure, i.e. the droplets of water, sodium and sodium hydroxide (produced in the sodium–water reaction). The erosion by the high-speed water droplet impingement has been a phenomenon interesting for both turbine and aircraft engineers. It has also attracted the attention of nuclear engineers because it leads to pipe wall thinning in the nuclear reactor system. The phenomena of liquid droplet impingement (Field et al., 1989), the mechanical load caused by the liquid droplet impingement (Heymann, 1968, 1969; Lesser, 1981) and the mass removal rate by the water droplet impingement (Heymann, 1979; Sanchez-Caldera, 1984; Springer, 1976) have been reported in the literature. The applicability of the reported results for sodium and sodium hydroxide (NaOH) is still to be investigated.

In the first part of this study the moving particle semi-implicit (MPS) method is applied to simulate the droplet impingement of water and sodium. The sodium hydroxide droplet impingement is not simulated because its physical properties (specifically, the speed of sound) are not available according to the knowledge of the authors. The mechanical load and impingement phenomena are given in this part. The second part of this study is devoted to develop a correlation which can predict the erosion rate by the impingement of sodium and sodium hydroxide. The popular correlations for erosion rate by the droplet impingement are first reviewed, and the extension of correlations is proposed.

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Nomenclature

A	coefficient in fitted correlation
B	coefficient in fitted correlation
C	sound speed, m/s
D	droplet diameter, mm
E	specific kinetic energy of droplet, ρV^2
G	constants in Tait equation, 299.6 MPa
H	impinged liquid height, i.e. impinged liquid volume on unit area, m
H_0	incubation duration expressed as impinged liquid height, m
H_v	hardness of material, Pa
J	J = 1 for lateral jet impingement; J = 0 for droplet impingement
k	constant in Heymann's correlation for impingement pressure
K	K = 1 for curved target; K = 0 for flat target
N_0	incubation duration expressed as the impinged times
P	pressure, Pa
R_e	maximum erosion rate, $(\partial Y/\partial H)_{\max}$
S	erosion resistance in Springer's correlation
S_0	erosion resistance for incubation duration
S_e	erosion resistance for maximum erosion rate
t	time, s
T	temperature, K
$\vec{u}$	velocity vector, m/s
V	impinging velocity, m/s
x	coordinates in wall-parallel direction, μm
Y	erosion depth, i.e. removed volume on unit impinged area, m
Γ	constant in Sanchez–Caldera's correlation
ν	kinematic viscosity, m²/s
μ	dynamic viscosity, kg Pa/s
ρ	density, kg/m³
ε_c	critical strain rate

Superscript

R	maximum erosion rate
N	incubation period

Subscripts

0	undisturbed condition
C	sound speed
l	liquid
P	pressure
ref	reference condition
V	impinging velocity
Na	sodium
μ	viscosity
ρ	density

2. Simulation of droplet impingement

2.1. Basics of simulation

The continuity equation, Eq. (1), and the momentum equation, Eq. (2), are solved in the computation:

$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\nabla - \vec{u} \tag{1}$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} + \vec{q} + \vec{g} \tag{2}$$

where $\vec{q}$ is the artificial viscosity which suppresses the numerical oscillation at the shockwave front and negligibly affects the flow elsewhere. The artificial viscosity formulation is a part of the MPS-AS (moving particle semi-implicit method for all speeds) method, which is utilized in the simulation of this paper. The details of the MPS-AS method can be found in Arai and Koshizuka (2009).

The compressibility of fluid is obtained from the equation of state. For water, the Tait equation (Cole, 1948)

$$\frac{P+G}{P_{\mathrm{ref}}+G} = \left(\frac{\rho}{\rho_{\mathrm{ref}}}\right)^N \tag{3}$$

is applied. In Eq. (3), P_{ref} is the reference pressure, 0.1013 MPa; ρ_{ref} is the water density at the reference pressure, 10^3 kg/m³; G is a coefficient which changes slowly along with the temperature, here it is assumed to be a constant, 299.6 MPa; N is a constant, 7.415 for pure water. The compressibility of liquid sodium is calculated with

$$\frac{\partial P}{\partial \rho} = C^2 \tag{4}$$

where C is the speed of sound which can be obtained with

$$C = a + bP + cP^2 \tag{5}$$

where a = 2503 m/s, $b = 1.05 \times 10^{-6}$ m/(s Pa) and $c = -2 \times 10^{-16}$ m/(s Pa²) (Shaw and Caldwell, 1985). Eq. (5) is obtained based on the experiments at temperature of about 150 °C. In order to consider the elevated temperature conditions, Eq. (5) is extrapolated by modifying the value of a

$$a = 2660.7 - 0.37667\,T - 9.0356 \times 10^{-5}\,T^2 \tag{6}$$

which is based on the dependence of speed of sound on temperature given by Fink and Leibowitz (1995). The surface tension on the impingement is not considered in the simulation because its effect is negligible when the impact velocity is high. All the simulations discussed in the present paper are two-dimensional (2D) ones.

2.2. Impinging conditions

In order to envelop the impinging conditions the impinging speed has been given with a wide range, from 100 m/s to 1,100 m/s. The effect of the droplet size is also investigated. Three droplet diameters, i.e. 1 mm, 0.1 mm and 0.01 mm, are involved in this study. The case where the 0.1 mm sized sodium droplet impinging on a rigid wall is defined as the reference case. The particles used in each simulation are uniform in size. The particle diameter is 60 μm when the droplet diameter, D, is 0.1 mm. And the particle size is adjusted to make sure the computation cost is not increased to unacceptable. For the convenience of later discussion we define the time t = 0 as the moment when the contact of the droplet and the wall starts. And the origins of the x and y coordinate are at the center of the impinged wall.

2.3. Simulated phenomena

The snapshots obtained in the simulation of the reference case are presented in Fig. 1. In case of the geometry is two- or three-dimensional (2D or 3D), the collision is one-dimensional (1D) at the very beginning before the shockwave could propagate in the sideway. The 2D or 3D effects appear after the oblique impact of the shockwave and the undisturbed fluid occurs, as shown in Fig. 2a. When the liquid obliquely impacts the shockwave front, the normal component of velocity disappears and the parallel component is left as it was. So the oblique impact causes a lower pressure than that resulted from the normal impact, and hence, leads to the non-uniform pressure distribution in the compressed liquid.