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Droplet generation during liquid jet impingement onto a horizontal plate

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ABSTRACT

In sodium-cooled fast reactors, liquid sodium leakage from piping may lead to fire accident. In the case that the liquid sodium is discharged as a liquid jet, a number of droplets are produced during liquid jet impingement on the structures; the surfaces of splashed droplets serve as a main reaction field of sodium combustion. In the present work, a liquid jet was emanated vertically downward from a circular nozzle hole onto a horizontal disk to measure the total amount and the maximum size of splashed droplets. It was found that the splashing rate was negligibly small when the liquid jet impinged as a continuous jet whilst a significant amount of liquid was splashed when the liquid jet impinged as a broken jet. Thus, a prediction method was first developed for the impact frequency of the primary droplets produced due to the jet breakup. It was then shown that a phenomenological model using the impact frequency and the impact Weber number as the important variables can predict the splashing rate well. It was also indicated that the size of the maximum splashed droplets was fairly proportional to the size of primary droplets.

1. Introduction

Liquid sodium is used as a coolant in many fast reactors because of its preferable features such as low capabilities of neutron moderation and absorption, high boiling point, high thermal conductivity, and low cost. However, the sodium is of high chemical reactivity. Consequently, if the liquid sodium leaks from the primary or the secondary system of a sodium-cooled fast reactor, the liquid sodium would react with the oxygen and moisture in the air to cause sodium fire incident [1]. Thus, the sodium fire analysis codes have been developed and validated extensively to evaluate the pressure and temperature transients in the reactor containment vessel after the onset of sodium leakage [2,3].

The discharged liquid sodium constitutes liquid pool and/or droplets in the containment vessel. The combustion intensity is commonly postulated higher when the liquid sodium exists as droplets since the surface area of the liquid sodium that serves as a reaction field of combustion is much larger for droplets [4]. Obviously, the total amount and size of liquid sodium droplets should be evaluated accurately in the sodium fire analysis codes.

In the case that the liquid sodium is discharged from piping as a liquid jet, a number of droplets are produced during liquid jet impingement onto the structures such as the wall, floor, ceiling, and so on. To the best of authors' knowledge, however, no systematic investigation has been made for the splashing during the liquid jet impingement. Consequently, considerable uncertainty is present in the amount and size of droplets postulated in the numerical analysis of sodium fire [5]. Thus, in the present work, experiments are conducted mainly to develop a phenomenological model for the splashing rate. As the basic experimental condition, water is used as the working fluid and it is emanated vertically downward from a circular nozzle hole; a stainless steel disk disposed horizontally is used as the target of the liquid jet.

As discussed above, the study for the splashing during liquid jet impingement is scarce, but many studies have been conducted for the behavior of liquid jet. It is widely known that a continuous liquid jet starts to breakup into droplets at a certain distance from the nozzle; this distance is commonly referred to as the breakup length. Rayleigh [6] analytically investigated the growth of axisymmetric disturbances formed on the surface of an inviscid jet, and Weber's analysis [7] showed that the breakup length of the liquid jet is inversely proportional to the jet velocity. Sterling and Sleiche [8] studied the liquid jets discharged into air; they analyzed the aerodynamic interaction between the jet and the ambient air to develop the equation expressing the growth rate of disturbance. Lin and Reitz [9] showed that the breakup length of the liquid jet can be expressed as a function of jet exit velocity.

Fig. 1 delineates the sections A, B and C that are of importance in determining the processes of splashing during liquid jet impingement onto a horizontal disk. The short descriptions of the three sections and the typical physical quantities characterizing each section are enumerated in Table 1. In the present work, the flow conditions of the liquid jet at the section A is specified in each experimental run and the

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Nomenclature

C_D	drag coefficient (dimensionless)
d_0	nozzle diameter (m)
d_{max}	diameter of maximum splashing droplets (m)
d_p	diameter of impacting droplet (m)
f	impact frequency (Hz)
f_{max}	maximum impact frequency (Hz)
f^*	dimensionless impact frequency (dimensionless)
L	fall height (m)
L_1	(minimum) breakup length (m)
L_2	maximum breakup length (m)
L^*	dimensionless fall height (dimensionless)
a	safety factor for breakup length (dimensionless)
b	safety factor for maximum impact frequency (dimensionless)
Q	volumetric flow rate of liquid jet (m^3/s)
Re	Reynolds number of liquid jet (dimensionless)
Sp	splashing rate (m^3/s)
Sp^*	splash ratio (dimensionless)
U_0	jet velocity at the nozzle (m/s)
U_1	jet velocity at the onset of breakup (m/s)
U_p	velocity of impacting droplet (m/s)
V_d	splashing rate per impact (m^3)
V_p	volume of impact droplet (m^3)
We	Weber number of liquid jet (dimensionless)
We_p	Weber number of impacting droplet (dimensionless)

Greek symbols

ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

g	gas phase
l	liquid phase

splash ratio (ratio of the droplet splashing rate to the jet flow rate) Sp^* is measured at the section C as the physical quantity of main interest. It would therefore be straightforward to correlate Sp^* in terms of the liquid jet state at the section A. It is however obvious that the liquid jet state at the section B is more closely related to Sp^*. In view of this, the following two-step approach is adopted in this work. In the first series of experiments, the liquid jet state at the section B is measured using a high-speed camera and it is correlated in terms of the liquid jet state at the section A. In this stage, several correlations are developed based on the findings of the jet breakup reported by the previous researchers. In the second series of experiments, Sp^* is measured and it is correlated in terms of the liquid jet state at the section B. Since splashing mainly takes place on the collision of primary droplets produced due to jet breakup, the impact Weber number We_p and the impact frequency f of the primary droplets are used as important variables in the correlation. To evaluate the surface area of the splashed droplets, not only the splashing rate but also the droplet size is important. Droplets of various sizes were splashed in the experiments. However, since the measurement of the droplet size distribution is not possible in the present experimental setup, the diameters of the maximum splashing droplets are measured.

In what follows, experimental apparatus is described in Section 2.

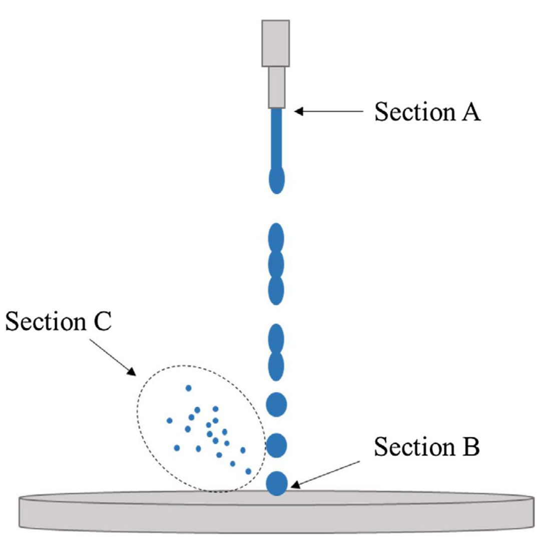

Fig. 1. Three sections characterizing the liquid jet impingement onto a horizontal disk.

The results and discussion of the first and second series of experiments are presented in Sections 3 and 4, respectively. Finally, Section 5 summarizes the main conclusions of this work.

2. Experimental apparatus

The experimental apparatus used in this work is shown schematically in Fig. 2. Since using liquid sodium is technically quite difficult, filtrated tap water was used as the test liquid because of its relatively low viscosity and high surface tension among ordinary liquids (the density, viscosity and surface tension are 828 kg/m^3, 0.227 mPa s and 156 mN/m for liquid sodium at 527 °C [10] whist 998 kg/m^3, 1.002 mPa s and 73 mN/m for water at 20 °C [11]). In the experiments, the test liquid was first supplied to the reservoir and then pressurized using the nitrogen cylinder. The pressure was measured using the pressure gauge equipped on the reservoir. The pressure in the reservoir and the opening of the needle valve on the discharge line were adjusted to set the flow rate at desired values. After the adjustments of the reservoir pressure and the needle valve opening, the magnet valve was opened to release the test liquid from the reservoir. During the experiment, the type-K thermocouple equipped on the reservoir accurate to within ± 0.1 K measured the liquid temperature and the turbine flow meter accurate to within ± 0.01 liter/min measured the liquid flow rate.

The cross-section of the nozzle is depicted in Fig. 3. The diameter of the flow channel was reduced gradually from 16 mm to the nozzle hole diameter d_0. The value of d_0 was a main experimental parameter and set to 1, 2 and 4 mm. The nozzle height was fixed while the elevation of the

Table 1
Descriptions of the three sections A, B and C.

Section	Description	Typical physical quantities	Nomenclature
A	Flow condition at the nozzle	Nozzle diameter Jet velocity at the nozzle Fall height	d_0 [m] U_0 [m/s] L [m]
B	State of liquid jet at the impingement	Diameter of impacting droplet Velocity of impacting droplet Impact frequency	d_p [m] U_p [m/s] f [s^{-1}]
C	State of splashed droplets	Splash ratio Diameter of maximum splashed droplets	Sp^* [–] d_{max} [m]