Systematic experimental investigation on the characteristics of molten copper fragmentation in water

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Abstract

During severe accidents in pressurized water reactors, thermal and hydraulic interactions play a crucial role in the Fuel-Coolant Interactions (FCI). Motivated to benefit the understanding on the fragmentation behavior of molten metallic fuel in water, in this study a series of simulated experiments is systematically conducted by injecting molten copper into a water pool. By adjusting parameters such as melt temperature, water temperature, melt penetration velocity, and water depth, the effects of these parameters on the fragmentation behavior of molten copper jet are investigated. It is found that water temperature determines the boiling mode during FCI, and at higher water temperatures, molten copper may not solidify and instead reach the bottom of the vessel in liquid form. When the melt temperature rises, the fragmentation process becomes less thorough, leading to an increase in the mass mean debris diameter. Higher penetration velocity of the molten metal results in smaller particles. A water depth greater than 70 cm has little effect on the fragmentation behavior. Weber number theory performs better in predicting the mass mean diameter of debris formed, comparing with the Rayleigh-Taylor and Kelvin-Helmholtz instability fragmentation theories.

Full Text

Preamble

Systematic Experimental Investigation on the Characteristics of Molten Copper Fragmentation in Water

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Abstract

During severe accidents in light water reactors, thermal and hydraulic interactions play a crucial role in Fuel-Coolant Interactions (FCI). To advance understanding of the fragmentation behavior of molten metallic fuel in water, this study systematically conducted a series of simulated experiments by injecting molten copper into a water pool. By adjusting parameters such as melt temperature, water temperature, melt penetration velocity, and water depth, we investigated their effects on the fragmentation behavior of molten copper jets. The results reveal that water temperature determines the boiling mode during FCI, and at higher water temperatures, molten copper may not solidify and instead reaches the bottom of the vessel in liquid form. As melt temperature increases, the fragmentation process becomes less thorough, leading to an increase in the mass mean debris diameter. Higher penetration velocity of the molten metal results in smaller particles. Water depth greater than 70 cm has little effect on fragmentation behavior. Weber number theory performs better in predicting the mass mean diameter of debris compared to Rayleigh-Taylor and Kelvin-Helmholtz instability fragmentation theories.

Key words: Copper melt; Fuel-Coolant Interactions; Severe accident; Fragmentation behavior; Debris bed

Nomenclature

Symbol	Description
c_p	Specific heat capacity (J/kg/K)
$c_{p,j}$	Specific heat capacity of the jet (J/kg/K)
$c_{p,w}$	Specific heat capacity of water (J/kg/K)
C	Undetermined coefficient of the equation
D	Characteristic length of Reynolds number (-)
d	Diameter of the unstable droplet (mm)
d_m	Mass mean diameter (mm)
d_v	Volume mean diameter (mm)
g	Gravitational acceleration (9.8 m/s^2)
H_w	Water depth (cm)
ΔP	Pressure drop across the debris bed (Pa)
Re_w	Reynolds number of water
T	Temperature (°C)

Symbol	Description
T_{boil}	Boiling temperature (°C)
T_m	Melt temperature (°C)
T_{m-p}	Melting point (°C)
T_i	Instantaneous interface temperature between the molten jet and water (°C)
T_{hn}	Homogeneous nucleation temperature (°C)
T_{min}	Minimum temperature difference for vapor film stability (°C)
T_h	Hot liquid/molten material temperature (°C)
T_c	Cold liquid/coolant temperature (°C)
T_w	Water temperature (°C)
U_f	Surface velocity of the fluid (m/s)
u	Relative velocity between the two fluids at the interface (m/s)
V	Melt penetration velocity (m/s)
v_{total}	Volume of the fragment (ml)
$v_{particle}$	Volume of particles (ml)
v_{water}	Volume of water (ml)
We	Weber number (-)
x_k	Mass fraction of fragments in the ith size interval to the total mass (-)
ε	Porosity of the debris bed (-)
ρ_c	Density of the coolant (kg/m^3)
ρ_f	Density of the fluid (kg/m^3)
ρ_m	Density of the molten metal (kg/m^3)
ρ_w	Density of water (kg/m^3)
μ_f	Viscosity of the fluid (Pa · s)
λ_{K-H}	Critical wavelength of the Kelvin-Helmholtz instability (mm)
λ_{R-T}	Critical wavelength of the Rayleigh-Taylor instability (mm)
σ_m	Surface tension of the jet (N/m)
σ_c	Surface tension of the coolant (N/m)
ϕ	Sphericity of the debris bed (-)

1. Introduction

During a catastrophic core meltdown incident in a Pressurized Water Reactor (PWR), liquefied core material is anticipated to penetrate the coolant as a high-velocity jet [**?**, **?**]. In the pool, melt fragmentation determines the subsequent accident progression. Inadequate fragmentation of corium may compromise the structural integrity of the reactor pressure vessel' s lower head, potentially leading to release of radioactive isotopes. Consequently, the fragmentation behavior of molten jets plays a crucial role in the defense-in-depth strategy of nuclear safety. Due to potential radiological threats and numerous uncertain negative impacts, Fuel-Coolant Interaction (FCI) has attracted significant attention from researchers [?, ?, ?, ?].

Numerous experiments have investigated FCI phenomena [?, ?, ?]. These experiments can be categorized into oxide/water systems, metal/water systems, oxide/sodium systems, and metal/sodium systems. In addition to actual core materials such as UO_2, UO_2-ZrO_2, and uranium, various simulated melt materials have been employed in FCI experiments, including Al_2O_3, Al_2O_3-FeO/Fe_2O_3, stainless steel, aluminum, copper, tin, zinc, and Wood' s metal [?, ?, ?, ?]. Despite extensive research on molten jet fragmentation, most studies have focused on low-temperature molten materials in cooling water, leaving a gap in systematic experimental research on high-temperature molten materials in cooling water. To address this deficiency, this paper presents an experimental study on the fragmentation of molten copper jets in water. The physical properties of copper are shown in Table 1 . Both qualitative and quantitative methods were employed to analyze the effects of melt temperature, water temperature, jet penetration velocity, and water depth on copper jet fragmentation behavior. The experimental data can be used for development and verification of severe accident analysis codes.

Preliminary studies have examined copper fragmentation behavior [?, ?]. The multi-physics coupling mechanisms governing liquid-phase metallic copper/cryogenic fluid interactions primarily manifest through synergistic thermal-hydraulic processes that enhance jet disintegration and oxide layer fracturing. This fragmentation behavior originates from: (1) phase-change-induced pressure fluctuations associated with vapor bubble dynamics; (2) multiphase interfacial instabilities amplified by thermal boundary layer interactions and momentum transfer; and (3) viscous dissipation effects within the melt-coolant mixing zone, particularly intensified by rapid vaporization of entrained coolant droplets.

However, past research on thermal-hydraulic interactions between molten copper and coolant remains limited, consisting primarily of qualitative studies with few instances, lacking systematic investigation of various parameter effects. To understand the influence of these parameters on copper jet fragmentation behavior, we conducted a quantitative study of debris bed characteristics. We designed an experimental setup using high-frequency heating equipment at Sun Yat-sen University to melt copper and inject it into a water pool [?]. High-speed cameras captured the fragmentation process, and fragment samples were collected. Measurements of accumulated debris and fragments were performed. Subsequently, we compared fragmentation processes and fragment samples under different parameters, analyzing their effects on copper fragmentation behavior in water in combination with previous research findings. Finally, we applied Kelvin-Helmholtz instability, Rayleigh-Taylor instability, and Weber number theory criteria to explain the fragmentation phenomenon of molten copper jets in coolant and analyze behavior modes under different conditions [?].

2.1 Experimental Apparatus

Fig. 1 [Figure 1: see original paper] illustrates the experimental apparatus for high-melting-point alloy fragmentation experiments. The apparatus includes: a stainless steel structural support, heating coil and crucible, ceramic plug with pulley assembly, a 47$×47×$150 cm rectangular water tank, a fragment collector, and a high-speed camera. Thermocouples installed in both the crucible and water tank track the thermal conditions of the molten material and coolant. The transparent vessel, constructed with heat-resistant glass, enables visual monitoring of the molten jet breakup process, with high-speed video recording capturing fragmentation dynamics. The thermocouples can measure temperatures up to 1300°C. The crucible bottom has an 8 mm diameter hole sealed with a ceramic plug under normal conditions. The alumina ceramic rod has a melting point exceeding 2000°C, making it reliable within the experimental temperature range. By pulling a steel wire, the ceramic plug can be lifted, allowing molten copper to inject into the water tank under gravity.

2.2 Experimental Procedure and Parameters

Before each experiment, we carefully weighed and placed copper in the crucible, then introduced water into the glass tank at the required depth. Several thermocouples were installed at relevant positions to measure the temperature of the heating copper and water tank in real time. When higher water temperature was required, the water was preheated to the predetermined temperature. We then started heating the copper.

When the melt temperature reached the predetermined value, the ceramic plug was pulled, allowing the melt to fall into the water while simultaneously triggering the high-speed camera to capture fragmentation behavior. Afterward, we collected samples for a series of measurements.

Table 2 shows the experimental parameters. In the table, water depth (H_w) is the distance from the water surface to the collector. Melt penetration velocity (V) refers to the velocity when the melt reaches the water surface, calculated by $V = \sqrt{2gh}$, where g is gravitational acceleration and h is the distance from the crucible outlet to the water surface.

Fig. 2 [Figure 2: see original paper] shows the schematic diagram of steam explosion possibility. The vertical axis represents coolant temperature T_c and the horizontal axis represents molten material temperature T_h. The high-probability zone for vapor explosion is called the Thermal Interaction Zone (TIZ). When experimental conditions approach this region, there is higher probability of steam film collapse and steam explosion occurrence. T_i represents the instantaneous interface temperature between the molten jet and water, T_{hn} is the homogeneous nucleation temperature, and T_{min} is the minimum temperature difference for vapor film stability. At atmospheric pressure, water' s homogeneous nucleation temperature T_{hn} is approximately 314.1°C [?].

T_i is calculated by:

$$T_i = \frac{T_h - T_c}{1 + \sqrt{\beta}} + T_c, \quad \beta = \frac{(\rho c_p k)_c}{(\rho c_p k)_h}$$

When $T_i = T_{min}$, the relationship between T_h and T_c is:

$$T_i = T_{min} = T_h - T_{sat} = 101 + 4.1(T_{sat} - T_c)$$

where T_{sat} is water saturation temperature. The boundaries of different regions can be obtained using equations (2) and (3).

2.3 Measurement Quantities

Experimental analyses focused on quantifying key particulate metrics including average particle dimensions, size distribution patterns, and assessing porosity and sphericity within aggregated fragments. By examining debris bed characteristics, researchers can identify correlations between solidification processes and molten stream dynamics.

2.3.1 Size Distribution of Fragments

After collecting and drying jet fragment samples, we used six sieves with sizes of 0.8 mm, 1.5 mm, 3.0 mm, 6.0 mm, 9.0 mm, and 12.0 mm, loading them into a vibrating machine for classification. Samples larger than 12.0 mm were referred to as agglomerates, while the rest were classified as fragments. By measuring the mass distribution of debris in each diameter interval, we determined reaction thoroughness. In this study, two mean diameters were calculated for subsequent analysis: volume mean diameter (d_v) and mass mean diameter (d_m).

The volume mean diameter is estimated as:

$$d_v = \sum_{i=1}^{n} d_i x_k$$

where d_i denotes the mid-diameter of fragments in the ith size interval and x_k is derived from the cumulative size distribution plot of fragments. The mass mean diameter (d_m) is calculated as the fragment size that equally splits the total debris mass.

2.3.2 Debris Bed Porosity

Porosity (ε) of the debris bed is the ratio of void volume to total bed volume, playing a key role in analyzing cooling behavior. In this study, porosity was determined using the drainage method [?, ?] and calculated as:

$$\varepsilon = \frac{v_{total} - v_{particle}}{v_{total}} = \frac{v_{water}}{v_{total}}$$

where v_{total}, $v_{particle}$, and v_{water} denote total debris bed volume, particle volume, and water volume, respectively.

2.3.3 Debris Sphericity

To quantitatively estimate debris morphology, sphericity (ϕ) is defined as follows [?, ?]:

$$\phi = \frac{\pi^{1/3}(6v)^{2/3}}{A}$$

where A represents particle surface area and v represents particle volume. According to the Ergun equation [?], fragment sphericity is calculated as:

$$\frac{\Delta P}{H_{pb}} = \frac{150(1-\varepsilon)^2\mu_f U_f}{\varepsilon^3(d_v\phi)^2} + \frac{1.75(1-\varepsilon)\rho_f U_f^2}{\varepsilon^3\phi d_v}$$

where parameters are defined as: ΔP (pressure differential), H_{pb} (bed height), ε (void fraction), μ_f (fluid viscosity), U_f (superficial velocity), d_v (volume-averaged particle diameter), ϕ (sphericity), and ρ_f (fluid density). Sphericity is determined through inverse modeling using the Ergun equation. A specialized test apparatus was developed to quantify fluid flow velocity and pressure gradient through particulate layers [?].

3. Experimental Results and Discussion

This section analyzes and compares experimental data. We captured images of molten metal jets injected into water at 0.05 s, 0.3 s, 0.6 s, 0.9 s, and 1.2 s, enabling observation of vapor interface evolution during copper fragmentation. Additionally, in experiments No. 1, 5, 6, 11, 12, and 15, we observed steam explosions, capturing instantaneous images at 0.0015 s intervals (1 frame).

3.1 Effect of Melt Temperature

Figs. 3-5 [FIGURE:3, FIGURE:4, FIGURE:5] depict the interaction process between molten copper jets and water at jet temperatures of 1100°C, 1200°C, and 1300°C. The figures show that size differences among molten metal jets are not significant across different metal temperatures. When jet breakup occurs, numerous bubbles generate along the jet sides (shown in red circles). The images reveal that fragments assume fixed shapes after traveling a certain distance, indicating they have cooled and primarily fall in solid state (shown in blue circles). Black smoke observed in some cases consisted of copper powder caused by steam explosions.

Figs. 6-8 [FIGURE:6, FIGURE:7, FIGURE:8] show the debris bed at jet temperatures of 1100°C, 1200°C, and 1300°C. The figures reveal that due to incomplete fragment cooling, agglomerates formed when water depth was within 70 cm. Additionally, fragments become larger with increasing melt temperature.

Fig. 9 [Figure 9: see original paper] shows debris bed physical properties. In this experiment, when water depth was not greater than 70 cm and jet temperature was set to 1300°C, most fragments had not completely solidified upon reaching the tank bottom. As they welded together and formed large agglomerates, measuring their size distribution was difficult.

Figs. 9(a)-(c) demonstrate that the debris bed exhibits a predominant particle size distribution peak within the 6-9 mm range. As jet temperature increases, the proportion of fragments with diameters in the 9-12 mm range increases. Notably, a 100°C temperature increment in molten material (from 1100°C to 1200°C) induces significant redistribution, manifesting as reduced prevalence of 6-9 mm particulates. This results in increased mass mean diameter of fragments, shown in Fig. 9(d). The curves for 1200°C and 1300°C are relatively close, possibly due to a marginal effect.

These results indicate that higher jet temperatures lead to less complete fragmentation, presenting a conclusion opposite to that for low-melting-point alloys. In previous studies on lead-bismuth eutectic (LBE) fragmentation [**?**], as melt temperature increased, fragment mass mean diameter decreased. This occurred because the LBE jet fragmented and cooled sufficiently in a short time after entering coolant, with higher melt temperatures delaying LBE solidification in water and enabling more thorough fragmentation. However, for high-melting-point metals like copper, after jet fragmentation, many fragments cannot be sufficiently cooled and may remain liquid. Stable film boiling during debris descent prevents some fragments from completely solidifying, causing them to merge and form larger fragments. As melt temperature increases, fragments become more difficult to solidify, leading to increased larger debris. Additionally, we observed steam explosions in some groups, which produced significant amounts of metal powder.

As indicated in Figs. 9(e) and (f), raising melt temperature renders the debris bed more compact and increases debris sphericity. As heat transfer between molten copper droplets and water occurs within the film boiling range, the vapor film surrounding molten copper droplets remains stable, resulting in slower heat transfer rates as these vapor films and steam bubbles provide isolation effects on molten copper. This makes the solidified copper surface smoother due to surface tension effects, and fragments tend toward spherical shapes.

3.2 Effect of Water Temperature

Fig. 10 [Figure 10: see original paper] shows the interaction process between copper molten jets and water under the following parameters: jet temperature of 1100°C, jet velocity of 3.13 m/s, water depth of 60 cm, and water temperatures of 25°C, 30°C, 40°C, 50°C, 60°C, and 70°C. The images show that jets undergo fragmentation and generate numerous bubbles after entering water. At lower water temperatures (25°C and 30°C), steam bubbles are smaller and more densely distributed. Droplets separated from the molten metal jet no longer change shape (shown in blue circles) and produce few steam bubbles in their surroundings, indicating they have solidified. At higher water temperatures (above 30°C), splintered droplets are encapsulated within a vapor film (shown in red circles) and continue deforming during descent, indicating they have not yet solidified. These metal droplets maintain their liquid state and continue generating numerous bubbles until reaching the tank bottom, where they accumulate and form large agglomerates.

Fig. 11 [Figure 11: see original paper] shows debris beds observed in the experiments. The vapor film surrounding molten metal droplets ruptures during descent, and molten metal cools and eventually accumulates at the bottom as fragments. From Fig. 10, it can be observed that jets underwent fragmentation when water temperature exceeded 30°C. However, in the catcher, these fragments consolidated into agglomerates, as shown in Fig. 11. This indicates that jets remained above copper' s melting point throughout contact with water, preventing solidification during descent. Metal jets and splintered droplets fell to the tank bottom and coalesced in liquid state.

Based on these observations, higher water temperatures increase the mass fraction of aggregates and inhibit fragmentation. After jet-water contact, rapid water heating and vaporization occur, and higher water temperature intensifies evaporation, leading to formation of thicker, more stable vapor films. Subsequently, due to certain fluid dynamic factors (such as Rayleigh-Taylor instability), vapor films rupture, resulting in fragmentation of the jet front and generation of numerous bubbles. Meanwhile, the vapor film at the molten material-coolant interface rapidly condenses, transitioning the main heat transfer mechanism from film boiling to nucleate boiling, with possibility of steam explosion. Although the overheated copper surface contacts coolant, the coolant cannot penetrate molten copper interior but rapidly evaporates on the overheated surface. Therefore, fragment surfaces remain relatively smooth and intact, resulting in higher sphericity of copper fragments (shown in red circles).

When water temperature rises to 40°C, fragmented jets re-solidify at the bottom. High water temperature kept this experimental set away from the Thermal Interaction Zone, as shown in Fig. 2. Vapor films can maintain around the jet for longer time in this case, significantly impeding heat exchange between jet and water and preventing effective solidification.

In previous LBE alloy studies, this debris bed morphology transformation occurred at 90°C water temperature [**?**]. This difference arises primarily because copper's melting temperature (1083°C) is much higher than LBE alloy's (125°C), maintaining film boiling on the copper-water surface for prolonged periods. Additionally, copper' s high thermal conductivity results in smaller temperature gradients on copper debris surfaces, leading to more stable interfaces.

3.3 Effect of Melt Penetration Velocity

In this section, jet temperature was set to 1200°C, water temperature to 25°C, and water depth to 110 cm. According to Dinh et al. (1999) [?], from a hydrodynamic perspective, relative velocity between two fluids significantly impacts the fragmentation process.

Fig. 12 [Figure 12: see original paper] shows interactions at jet velocities of 3.13 m/s, 3.42 m/s, and 3.70 m/s. The images reveal that fragmentation occurs within the first 15 cm after jet entry. The fragmentation process shows no significant variation across different penetration velocities. Similarly, the number and size of bubbles produced during this process remain largely unchanged.

Fig. 13 [Figure 13: see original paper] shows fragment samples obtained, demonstrating debris beds formed by the collector at the tank bottom for corresponding groups in Fig. 12. No significant differences appear among debris bed morphologies at different penetration velocities.

Fig. 14 [Figure 14: see original paper] illustrates debris bed physical properties. Higher molten copper jet penetration velocity strengthens fragmentation effects, resulting in smaller fragmented products. This is consistent with previous LBE experiments [?]. Considering deviation, penetration velocity exerts no significant impact on debris bed porosity or fragment sphericity, as shown in Figs. 14(c) and (d). Based on previous studies [?], fragment sphericity is greatly influenced by thermal factors. Under conditions where stacking method and fragment shape are similar, when jet penetration velocity is higher, fragmented particle diameter decreases approximately proportionally, while debris bed morphology does not change significantly.

3.4 Effect of Water Depth

In this section, jet temperature was set to 1200°C, water temperature to 25°C, and penetration velocity to 3.13 m/s.

Fig. 15 [Figure 15: see original paper] shows the interaction process between molten copper jets and water at water depths of 60 cm, 110 cm, and 130 cm. The images reveal no significant difference in fragmentation process among different water depths, and the number and size of bubbles generated during fragmentation are also not significantly different. A steam explosion occurred when water depth was 110 cm.

Fig. 16 [Figure 16: see original paper] presents debris bed morphology at different water depths. The debris bed morphology at 60 cm water depth is markedly distinct from that at 110 cm and 130 cm. At 60 cm water depth, fragments did not cool sufficiently, resulting in large agglomerate formation at the bottom. Debris bed morphologies at 110 cm and 130 cm water depths are similar.

Fig. 17 [Figure 17: see original paper] illustrates debris bed physical properties. As water depth increases, the proportion of debris with diameters of 3-9 mm decreases, while debris with diameters of 9-12 mm increases. This may occur because during falling, fragmented jets have not yet solidified, and some small fragments fuse to form larger ones.

As shown in Figs. 17(c) and (d), water depth exerts minimal impact on debris bed porosity. Nevertheless, fragmented particle sphericity demonstrates a slight increasing trend with deeper water. This might be because in relatively shallow water, fragments cannot completely cool. When these uncooled molten copper droplets reach the fragmentation product collector, they alter the original shape, reducing fragment sphericity. However, since debris bed formation does not change significantly, debris bed porosity remains largely unchanged.

3.5 Discussion on Triggering Factors of Steam Explosion

Fig. 18 [Figure 18: see original paper] shows specific steam explosion processes with screenshot intervals of approximately 0.0015 seconds (1 frame) in experiments No. 1, 5, 6, 11, 12, and 15. Steam explosions typically start with a fragment, followed by shock wave propagation to surrounding fragments, causing them to explode as well, resulting in a chain reaction. These explosions produce large amounts of metal dust in the water tank.

In Section 3.2, which explored water temperature effects on molten jet fragmentation behavior, jet temperature was controlled at 1100°C. When water temperature was set at 25°C and 30°C, steam explosions were observed. However, at higher water temperatures, the predominant jet reaction mode in water was stable film boiling, and metal droplets fell in liquid form without steam explosions.

In Section 3.1, when water temperature was set at 25°C and jet temperature was 1100°C, steam explosions occurred in all experiments. Some experiments with 1200°C jet temperature also observed steam explosions, while no steam explosions occurred at 1300°C. At room temperature water, as molten metal temperature decreases, the relationship between water and molten metal becomes more similar to the Thermal Interaction Zone, leading to higher steam explosion probability (as shown in Fig. 2). Under these conditions, melt temperature directly influenced steam explosion occurrence.

3.6 Comparison Between Experimental Results and Fragmentation Theories

When molten copper jets enter cooling water, the interface between molten copper and cooling water experiences fluctuations due to external oscillation wave instability. Wavelength growth easily leads to vapor film rupture, exacerbating molten copper fragmentation. These external oscillation waves primarily include Kelvin-Helmholtz instability (K-H instability) and Rayleigh-Taylor instability (R-T instability).

Kelvin-Helmholtz instability refers to instability at the interface between two different fluids with velocity differences or within a continuous fluid with shear velocity. The most-unstable wavelength of K-H instability λ_{K-H} is given by [?]:

$$\lambda_{K-H} = \frac{2\pi\sigma_m(\rho_m + \rho_c)}{u^2\rho_m\rho_c}$$

where ρ_m represents molten metal density (kg/m^3), ρ_c is coolant density (kg/m^3), σ_m is molten metal surface tension (N/m), and u represents relative velocity between the two fluids at the interface, which in this case is the melt penetration velocity V.

Rayleigh-Taylor instability originates from disparity in inertia forces between two fluids at the surface wave, predominantly occurring at the foremost part of the melt jet when it vertically intrudes into the interface during melt-coolant interactions. The wavelength related to the most rapid growth rate of R-T instability can be represented by [?]:

$$\lambda_{R-T} = 2\pi\sqrt{\frac{3\sigma_m}{(\rho_m - \rho_c)g}}$$

On the contact surface between molten material and coolant, shear force from relative fluid velocity balances surface tension on molten metal droplets. Disruption occurs when this equilibrium breaks. To predict disruption occurrence, the Weber number (We) is an important dimensionless parameter, defined as [?]:

$$We = \frac{\rho_c V^2 d}{\sigma_m}$$

where We is the Weber number, V is the velocity (m/s) at which molten metal contacts the coolant (the melt penetration velocity in this experiment), σ_m denotes molten metal surface tension (N/m), and d is molten metal droplet diameter (mm).

Saito et al. proposed the following Weber number calculation method based on fragment mass mean diameter [?]:

$$We = C Re_w^{0.5}\frac{\mu_w}{\mu_m}$$

where C is an empirical coefficient, μ_w represents water dynamic viscosity, μ_m represents molten material jet dynamic viscosity, and Re_w represents water Reynolds number at characteristic length D, calculated by:

$$Re_w = \frac{\rho_w V D}{\mu_w}$$

where V is molten material jet penetration velocity and D can be viewed as molten metal droplet diameter d in this context. The molten metal droplet diameter is assumed equal to fragment mass mean diameter. After fitting, coefficient C was taken as 0.02. Combining Eqs. (10), (11), and (12), d can be expressed as a function of V:

$$d = 8 \times 10^{-6} (\rho_w \mu_m)^{0.5} V^4$$

Fig. 19 [Figure 19: see original paper] compares experimental results with R-T instability, K-H instability, and Weber number theories. The graph shows that, in contrast to other fragmentation theories, Weber number theory better predicts fragment mass mean diameter. This may be because Weber number accounts for interaction between molten jet surface tension and water shear force.

4. Conclusions

To gain deeper understanding of molten fuel fragmentation behavior, we conducted simulated experiments introducing molten copper into water with varying melt temperatures, water temperatures, penetration velocities, and water depths. Our extensive discussions covered the impact of these parameters on jet fragmentation processes, debris bed morphology, fragmentation product forms, fragment size distribution, fragment mass mean diameter, fragment bed porosity, and fragment particle sphericity. By comparing experimental results with theoretical predictions, we drew the following conclusions:

1. As molten material temperatures rise, fragmentation products become larger, resulting in denser fragment beds and more spherical particles.
2. As water temperatures increase, the vapor film between molten copper jets and water stabilizes, causing large agglomerates to form at the bottom.
3. Greater melt penetration velocity intensifies fragmentation effects, producing smaller fragments. However, it does not significantly affect debris bed porosity or fragment sphericity.
4. Except when large aggregates form at shallow water depths and high copper superheat, water depth has little impact on melt jet fragmentation behavior.
5. Weber number theory outperforms Rayleigh-Taylor and Kelvin-Helmholtz instability theories in predicting debris mass mean diameter.

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Note: Figure translations are in progress. See original paper for figures.