Experimental Investigation on Trigger Dynamics of Molten Droplet under External Disturbance Pressure during Fuel-Coolant Interaction

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Abstract

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Full Text

Preamble

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Abstract

Fuel-coolant interaction (FCI) remains one of the most complex challenges in severe accident research, with the triggering process representing a critical aspect that may govern subsequent fine fragmentation and potential steam explosions. In this study, the evolution characteristics of droplet-water interactions under external disturbance conditions were investigated using a self-designed FCI experimental setup. Analysis of experimental observations reveals that cavity formation helps reduce drag force on the droplet, thereby increasing its peak velocity. However, external disturbance pressure can disrupt the cavity, leading to a reduction in the droplet' s peak velocity. Furthermore, it was found that an increase in external disturbance pressure tends to raise the peak value of the droplet expansion rate, thereby promoting the fine-fragmentation process. This effect holds regardless of the initial droplet temperature, coolant temperature, or even when using droplet materials such as lead, which are generally considered unfavorable for steam explosions. Comparative analyses indicate that higher external disturbance pressure may shorten the triggering time of the droplet surface and enhance trigger intensity. These findings provide important phenomenological insights for further investigation of triggering mechanisms in the initial stage of fuel-coolant interactions.

Keywords: External Disturbance Pressure; Molten Droplet; Transient Velocity; Expansion Rate; Fuel Coolant Interaction

1. Introduction

In the event of a severe accident at a nuclear power plant, loss of coolant may prevent adequate core cooling, potentially leading to core meltdown. If high-temperature core material subsequently contacts low-temperature coolant directly, a steam explosion may occur. Zhong et al. [1] simulated pressure loads generated by ex-vessel steam explosions in a PWR cavity, demonstrating that in worst-case scenarios, pressure loads can exceed typical reactor cavity wall design capacities. The resulting shock wave could compromise reactor structural integrity and release radioactive materials into the environment, posing serious safety risks to both the nuclear power plant and personnel [2-5]. This phenomenon, known as fuel-coolant interaction (FCI), and its potential consequences have drawn significant attention from nuclear safety researchers [6-10].

FCI is relevant not only for light water reactors but also for sodium- and lead-cooled fast reactors, where understanding its progression is essential for the

design and licensing of Generation IV reactor concepts [11]. For instance, in the case of an unprotected loss-of-flow or transient overpower accident in such reactors, a core disruptive accident (CDA) could cause fuel relocation and ejection of molten corium into a volatile coolant pool [12]. During this process, the corium may undergo extensive fragmentation due to thermal and hydrodynamic instabilities [13, 14]—a behavior that differs from FCI in water-cooled reactors owing to differences in thermal and fluid properties. Moreover, in certain designs such as annular fuel configurations for lead fast reactors, fuel pin failure could trigger interactions between high-momentum jets—containing ejected fuel in the form of solid grains or molten droplets—and metallic coolant droplets. The outcomes of such interactions are associated with reactor safety issues known as pin failure propagation [15]. Therefore, understanding the mechanisms and characteristics of each FCI stage is essential for preventing steam explosions.

The FCI process can be broadly divided into four key stages [16, 17]: pre-mixing, triggering, propagation, and expansion. Over the past few decades, Li et al. [18] observed through experiments that molten material temperature significantly affects vapor explosion behavior and pressure, and that increasing coolant temperature reduces vapor explosion pressure—a finding later corroborated by Huang et al. [19]. Furthermore, based on experiments involving low-temperature molten tin alloy droplets entering water, Li et al. [20] proposed a physical mechanism in which coolant trapped inside the molten material may be heated and vaporized, leading to vapor explosion; however, this phenomenon is not observable through visualization methods. Regarding the pre-mixing stage, Li et al. [21] also studied the settling behavior of high-temperature particles in coolant liquid, concluding that film boiling on the particle surface slows particle settling speed as either particle or coolant temperature increases, which may significantly influence the subsequent triggering process. Rather than focusing on hydrodynamic effects, Lin and Cao [22] analyzed the MIXA experiment using simulation codes and recommended using a thermal fragmentation model for high-temperature molten droplets under low Weber number conditions.

In recent years, numerous FCI-related studies have been conducted to understand fragmentation mechanisms, steam explosion potential, and debris bed characteristics in light water-cooled reactors and liquid metal-cooled fast reactors. Johnson et al. [12] investigated interactions between metallic corium jets and sodium at the MELT facility. Both X-ray imaging and debris analysis indicated that crust formation induces spontaneous thermal fragmentation. Rao et al. [14] studied fragmentation of simulated corium in sodium using real-time X-ray imaging and concluded that the potential for energetic interaction is lower in sodium than in water. Xiang et al. [5] focused more on debris bed characteristics resulting from fuel-coolant interactions, analyzing effects of jet breakup and droplet fragmentation for various simulant materials. Cheng et al. [23] conducted Coolant-Injection (CI) experiments comparing outcomes of delivering water into Bi-Sn-In alloy and lead-bismuth eutectic (LBE) alloy, contributing to understanding of CDAs in sodium-cooled fast reactors. Choi et al. [24] performed numerical simulations of jet breakup by adopting an improved surface

tension model in two typical configurations, verifying that these SPH simulation results align with experimental data. These findings offer valuable insights and suggest a possible relationship between droplet motion and steam explosion.

The triggering stage plays a critical role in determining steam explosion probability and severity. After passing through the pre-mixing stage, high-temperature melt forms droplets of various sizes, each enveloped by a stable vapor film due to heat exchange with the coolant. At this point, internal or external disturbances can cause vapor film collapse, leading to local high pressure and triggering [25-27]. Internal disturbances—known as self-triggering—can result from cooling of the melt itself. When melt temperature drops below the film boiling temperature, vapor film stability is compromised, leading to triggering [28]. External triggering arises from factors such as ambient pressure changes, melt-melt collisions, coolant convection, or entrainment. Such disturbances force coolant into contact with the melt, initiating the trigger [29]. Therefore, understanding vapor film collapse is essential for studying steam explosion triggering [30].

To elucidate triggering stage mechanisms, researchers have conducted extensive experimental studies. Early work focused primarily on melt triggering in the absence of external disturbances. Dullforce [31] performed numerous experiments on single tin droplet-water interactions and compiled trigger strength data across different droplet and water temperatures, leading to development of a temperature interaction zone (TIZ) for tin and water. Within this TIZ, steam explosions occur spontaneously when tin droplets enter water, with TIZ boundaries strongly influenced by physical properties and droplet mass. Kouraytem [32] investigated interactions between Field' s metal droplets and cooling water at varying initial temperatures, finding that the lower threshold temperature for steam explosion was approximately 400 °C. Rayleigh-Taylor instability was identified as the main cause of vapor-liquid interface instability, with its wavelength decreasing as steam explosion intensity increased. Watts [33] conducted single-droplet experiments using tin, gallium, and bismuth, focusing on vapor film collapse and subsequent droplet fragmentation. Results indicated that materials with low surface tension and density experience significantly intensified vapor explosions. Meanwhile, Corradini [34] analyzed FCI experiments performed by Nelson [35] at Sandia National Laboratories, concluding that: (1) higher water temperatures stabilize the vapor film, thereby suppressing triggering; (2) non-condensable gases such as hydrogen in the vapor film can inhibit self-triggering in some droplets; and (3) external triggers can induce steam explosions in droplets that do not self-trigger.

To further clarify melt triggering mechanisms, researchers have also performed vapor film rupture experiments under externally applied disturbances. Bankoff [36] studied vapor film collapse of Freon and ethanol on an electrically heated nickel tube using a pressure step method, with step magnitudes of 0.1-0.5 MPa and pulse rise times ranging from 80 s to 344 ms. They found that vapor film rupture may occur when the pressure step exceeds three times the ambient pressure and the pulse rise time is less than 150 ms. Inoue [37] conducted vapor film

rupture experiments on an electrically heated platinum foil, also using a pressure step method with magnitudes of 0.1-1.5 MPa and rise times of 0.1-7.5 ms. Partial vapor film collapse was observed at pressure steps around 0.5 MPa, with the extent of collapse increasing as pulse rise time decreased. Naylor and Patrick [38] carried out a series of vapor film rupture experiments using a hemispherical brass rod at 770 K immersed in a liquid pool, studying both self-triggered and externally triggered conditions. Their results indicated that vapor film collapse occurs when the sum of melt surface roughness and the amplitude of the vapor-liquid interface wave exceeds the average vapor film thickness.

Recent experimental analyses of FCI have been conducted by various research groups. For specific details, refer to Table 1 .

Table 1. Experimental Research on Fuel-Coolant Interaction

Region (Institution)	Experimental Facility or Project	Triggering Conditions	Objective
France (Scalian, Lab & CEA) & Japan (JAEA)	MELT facility	Self-trigger	Interactions between metallic corium jets and sodium
India (Homi Bhabha National Institute)	MFCI facility	Self-trigger	Fragmentation of simulated corium in sodium
Sweden (Royal Institute of Technology)	DEFOR-M facility	Self-trigger	Characteristics of a debris bed resulting from FCI
China (Sun Yat-Sen University)	PMCI facility	Self-trigger	Coolant Injection-mode FCI
China (Xi' an University)	Debris formation experimental platform	Self-trigger	Formation of the debris bed

Region (Institution)	Experimental Facility or Project	Triggering Conditions	Objective
China (Shanghai University of Electric Power)	External trigger experimental platform	Self-trigger & external trigger	Characteristics of triggering stage mechanism

Regarding small-scale experiments involving external pressure disturbances, prior studies have shown that different geometries and pressure dynamics significantly influence vapor film rupture under constant temperature conditions. However, the mechanism of external triggering for droplet-shaped melts under high-temperature conditions remains unclear. To better understand this issue, further investigation into the evolution characteristics of the melt during the triggering stage is necessary.

In this study, a small-scale experimental facility was established to investigate interactions between high-temperature melts and low-temperature coolant using a visualization approach. The setup is designed to support FCI research under externally applied disturbances. By analyzing and comparing characteristic melt-water interaction phenomena, this work quantifies variations in transient melt velocity, expansion rate, triggering pressure peaks, and fragment morphology under various conditions. These findings provide deeper insight into the triggering mechanisms of molten droplets during FCI.

2.1 Experimental Facility

The experimental facility used in this study, illustrated in Fig. 1 [Figure 1: see original paper], was designed with reference to previous experimental setups [39-41] and adapted to meet the specific objectives and technical requirements of the present research. The system consists of the following major components: a vacuum graphite electrode furnace, a melt-release mechanism, a transparent water tank, temperature and pressure acquisition instruments, a high-speed camera, and an external disturbance device.

The vacuum graphite electrode furnace features a double-layer annular structure heated by five graphite electrodes [42], with a maximum design temperature of 2200 °C. A graphite crucible placed inside the furnace is used to melt the metal, while the temperature at the center of the heating zone is monitored using an infrared pyrometer. The furnace exterior is lined with graphite wool insulation to minimize heat loss. Additionally, a vacuum system is employed to prevent oxidation of the graphite electrodes and the molten material.

The melt-release device consists of a graphite support rod and an electric lift, allowing precise and automated control of the melt release rate. During the

metal melting process, the graphite rod is lowered via a control cabinet so that its conical tip seals tightly against a corresponding conical outlet at the bottom of the graphite crucible, preventing leakage. Once the metal reaches the target temperature, the graphite rod is retracted upward by the control system, enabling the melt to be released and fall freely under gravity.

The water tank is a rectangular stainless-steel frame fitted with transparent viewing panels. To facilitate observation and data recording, the front and rear sides are equipped with pressure-resistant acrylic windows. The left-side wall features two rows of ports for mounting pressure transmitters and thermocouples. Fig. 2 [Figure 2: see original paper] shows the vertical arrangement of the temperature and pressure measurement points. The internal dimensions of the tank are 250 mm (length) × 250 mm (width) × 1800 mm (height). Specifications for the measurement equipment used in this study are provided in Table 2 .

Table 2. Detailed Information of Measuring Equipment

Equipment	Measuring Range	Accuracy	Response Time
Thermocouple (K-type)	0-100℃	$±$0.1%	-
Pressure Transmitter (YMC-41)	0-1 MPa	$±0.1×$1080 (full resolution)	0.1 ms

The temperature and pressure acquisition system consists of thermocouples, pressure transmitters, and a corresponding data acquisition platform, enabling comprehensive recording of temperature and pressure variations during melt settling in water. Additionally, a high-speed camera capable of frame rates up to 200,000 fps, along with its supporting software, meets the requirements for dynamic recording and image processing of the melt descent process.

The external disturbance device, shown in Fig. 3 [Figure 3: see original paper], comprises a gas cylinder (1), a pressure reducing valve (2), a trigger switch (3), a pressure relief switch (4), piston components (5), pressure transmitters (6), and other associated parts. Its operating principle involves regulating high-pressure gas from the cylinder via the pressure reducing valve. The regulated gas is then delivered through the trigger switch to the piston assembly located at the bottom of the water tank, generating a controlled external pressure pulse. This system enables precise generation of millisecond-scale pressure disturbances of up to 3 MPa within the water environment, offering a safer and more stable alternative to traditional methods of introducing explosive disturbances [43, 44].

2.2 Case Details and Data Processing

This study focuses on the influence of external disturbances on the evolution characteristics of droplets during the triggering stage. A comparative experimen-

tal analysis of the transient velocity and expansion rate of droplets with and without external disturbance provides supporting evidence for understanding the droplet triggering mechanism. The materials and experimental conditions used are listed in Table 3 and Table 4 , respectively. The experimental procedure is as follows: Prior to each test, a predetermined amount of cooling water is added to the tank to maintain a consistent droplet falling height across all cases. The initial droplet temperature, water temperature, and external disturbance pressure are then set according to the requirements of each test condition. Once the target temperatures are reached, the melt-release device is activated to discharge the droplet. Data recording is simultaneously initiated using the temperature and pressure acquisition system and the high-speed camera.

Controlling uncertainties in FCI experiments remains challenging due to the complex, coupled hydrodynamic and thermal effects occurring within extremely short timeframes. Therefore, strict pre-test protocols are essential. During pre-test preparation, an infrared pyrometer is used to accurately monitor the melt temperature in the furnace. The molten droplet is released only after the temperature has remained stable for at least 15 minutes, limiting the maximum relative error in droplet temperature to within 5%. To minimize impurities, all tests employ high-purity materials: Sn-99.99%, Pb-99.999%, and a Pb-Sn alloy with a composition of 50:50 wt%. These high-purity materials ensure consistent thermal properties of the melt.

Although droplet size (particularly droplet shape) cannot be precisely controlled and may influence local heat transfer and related processes, certain measures are taken to improve repeatability. As with other internationally recognized FCI experiments (e.g., MISTEE by KTH, KROTOS by CEA, TROI by KAERI, and SIGMA by UCSB), perfect reproducibility is not always achievable. Nevertheless, to promote droplet uniformity, an adjustment rod is used to regulate both the release frequency and droplet diameter. During preliminary tests, the rod is rotated until a stable stream of freely falling droplets is achieved—set here at 100 drops per minute. The rod position corresponding to this stable condition is marked and used in all subsequent tests to ensure essentially consistent droplet size.

Table 3. Main Properties of Experimental Materials

Experimental Material	Density (g/cm^3)	Melting Point	Boiling Point	Specific Heat Capacity ($J/(kg \cdot K)$)
Lead-tin alloy	-	-	-	-

Table 4. Experimental Conditions

Experimental Material	Melt Temperature (℃)	Water Temperature (℃)	External Disturbance Pressure (MPa)
Lead-tin alloy	-	-	-

Fig. 4a [Figure 4: see original paper] shows two consecutive frames captured during droplet entry into water, with a time interval of 0.1 ms between frames. The settling velocity is determined from close-range experimental observations. The transient velocity of the droplet is estimated by calculating the average velocity between two consecutive images, defined as the ratio of relative displacement to the time interval. The leading-edge position of each droplet is tracked using high-speed video, and the displacement (denoted as Δy) over a 0.1 ms interval (corresponding to the system response time) is recorded. The corresponding velocity is therefore given by Eq. (1).

Fig. 4b shows the droplet shape at a specific instant during water entry. Although the shape change of the droplet within the mixing region cannot be precisely quantified from the image, the boundary of the interaction zone is clearly distinguishable. The instantaneous droplet diameter is therefore approximated based on an equivalent circular area, and the droplet expansion rate is taken as the average expansion rate between two consecutive images. The equivalent diameter of the molten droplet is estimated using Eq. (2), where D and D represent the horizontal and vertical diameters of the droplet, respectively, and D_d denotes the equivalent diameter used to characterize the size of the irregularly shaped droplet.

The droplet expansion rate is determined by analyzing high-speed video footage of the vapor film-water interface evolution. Using the equivalent diameter method, the instantaneous droplet diameter is measured over a 0.1 ms interval (system response time). The corresponding expansion rate is therefore given by Eq. (3).

Experimental measurements are inevitably subject to discrepancies from true values due to factors such as instrument accuracy, measurement techniques, and test conditions. In this study, measurement errors are categorized as either direct or indirect. For parameters with direct measurement errors, the true value is expressed as Eq. (4):

$$X_{\text{real}} = X \pm \delta_X$$

where X_{real} is the true value of the parameter; X is the measured value; and δ_X is the absolute error.

The physical variables directly measured are X_1, X_2, X_3, ···, X . Since these are independent variables, the indirectly measured physical variable G is given by:

$$G = S(X_1, X_2, X_3, \dots, X_n)$$

For parameters with indirect measurement errors, based on error transfer theory, the error of the physical variable by indirect measurement can be calculated by Eq. (6):

$$\delta_G = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial S}{\partial X_i} \delta_{X_i} \right)^2}$$

where δG *is the error of the indirectly measured physical variable;* δ\{X_i\} is the error of direct measurement value X_i; and S/ X_i is the error transfer coefficient.

Therefore, the relative error of the indirectly measured physical variable G during the experiment is given by Eq. (7):

$$\psi_G = \frac{\delta_G}{G}$$

Based on the error calculation methodology described above, the maximum relative errors for key experimental parameters—including droplet mass, droplet temperature, water temperature, pressure variations during interaction, external disturbance pressure, transient droplet velocity, and droplet expansion rate —are presented in Table 5 .

Table 5. Relative Errors

Parameters	Maximal Relative Error
Droplet mass	-
Droplet temperature	-
Water temperature	-
Pressure change during interaction	-
Temperature change during interaction	-
External disturbance pressure	-
Transient droplet velocity	-
Droplet expansion rate	-

3.1 Typical Phenomena

The A1 condition, characterized by a lead-tin alloy temperature of 300 °C, a water temperature of 20 °C, and the absence of external disturbance pressure, is illustrated in Fig. 5a [Figure 5: see original paper]. The penetration event is of short duration. Prior to water contact, the droplet falls in a regular shape. The immense temperature difference upon impact induces violent heat transfer,

resulting in formation of a vapor film encapsulating the droplet. Subsequent expansion of the vapor is observed in both horizontal and vertical directions, yielding a vapor pocket. Pronounced separation of this pocket from the droplet occurs in the vertical direction, in contrast to more limited horizontal development. Air entrainment, attributed to the droplet-water velocity difference, was also observed. As presented in Fig. 5b, the vapor pocket subsequently undergoes constriction at its center, with the majority of entrained air migrating backward under aqueous surface tension until atmospheric release.

Fig. 6a shows the transient velocity variation of a droplet. In the plot, line a-b corresponds to the droplet' s velocity change in air. The water surface is indicated by a solid black line, and the moment the droplet crosses this line is defined as t = 0 s for simplicity. Line b-c reflects velocity variation during initial penetration into water. Upon contacting the water, the droplet experiences deceleration due to both hydrodynamic drag and an upward force caused by localized steam generation at the leading edge, leading to pressure rise. As steam generation increases over time, pressure at the droplet front rises, forcing vapor to move rearward and form an airbag along with entrained air. As demonstrated in our previous study [45], this vapor envelope reduces drag, resulting in velocity recovery, shown as line c-d. When the vapor shifts backward, the droplet' s leading edge re-establishes contact with liquid water. Although some steam continues to form, its quantity is reduced and stability is diminished. Consequently, hydrodynamic resistance increases again, and droplet velocity decreases, as seen in line d-e. Finally, as the droplet detaches from the airbag and undergoes further deformation, its velocity continues to decline until stabilizing, represented by line e-f.

Fig. 6b presents the expansion rate history of the same droplet. Line a-b corresponds to the period from initial water contact to full submersion. Vapor generated by intensive droplet-water heat transfer causes droplet expansion. However, as the immersion process initially occurs at low velocity and the droplet's wetted area increases only gradually, a stable interaction state is not yet reached. Thus, the expansion rate increases only slowly in this stage. Line b-c corresponds to a faster immersion phase, during which the airbag at the droplet' s leading edge begins to collapse. The droplet may also undergo expansion and fragmentation upon contact with cold water, leading to a sharp rise in expansion rate. Over time, however, the droplet cools and the airbag detaches, causing the expansion rate in line c-d to decline gradually toward zero.

3.2 No External Disturbance Pressure

Fig. 7a [Figure 7: see original paper] shows the transient velocity of a single droplet at different temperatures upon water contact. As droplet temperature increases, both the duration of acceleration and the peak velocity are extended and elevated, respectively, raising the overall velocity level. With constant water temperature, a hotter droplet induces faster and more extensive water evaporation, producing more vapor. This influences the process in two ways: first,

enhanced evaporation accelerates cavity formation, prolonging the droplet' s fall within the cavity. As previously analyzed, the cavity reduces direct contact between the droplet and water, leading to lower resistance and thus higher droplet velocity. Second, more vapor accumulates in the droplet' s wake region [46], providing additional downward propulsion.

Fig. 7b presents the droplet expansion rate across different droplet temperatures. As temperature rises, the growth duration of the expansion rate after water entry is prolonged, while the peak expansion rate initially increases and then decreases. At 300 °C, the droplet is rapidly cooled upon contact, resulting in only a minor expansion rate increase. At 400 °C, 500 °C, and 600 °C, the droplet enters an unstable film boiling regime, where intermittent vapor film collapse causes repeated water contact and fine-scale fragmentation, leading to large fluctuations in expansion rate. At 700 °C and 800 °C, stable film boiling occurs, enveloping the droplet in a persistent vapor film that protects it during descent until cooling. Here, the expansion rate increases smoothly and exhibits the longest duration among all cases.

Fig. 7c illustrates transient thermal-hydraulic behavior and resulting debris fragments at droplet temperatures of 300 °C, 500 °C, and 700 °C. At 300 °C, the droplet' s leading edge develops a conical protrusion, and the resulting debris fragment is smooth and elliptical. At 500 °C, the leading edge becomes flared and spiky, and the debris body appears rough and curled. At 700 °C, the leading edge reverts to a smooth elliptical shape, while debris fragments form slender, flake-like structures with spiky surfaces. Peak pressures measured by a high-frequency dynamic pressure transducer further support these observations, showing a trend of initial increase followed by decrease with rising droplet temperature. The maximum pressure, 0.022 MPa, occurs at 500 °C, as summarized in Table 6 . Additionally, by comparing the timing of transient velocity and expansion rate, it is noteworthy that their peak values occur simultaneously.

Table 6. Peak Pressure at Different Droplet Temperatures

Time (ms)	Peak Pressure (MPa)
-	-

Fig. 8a [Figure 8: see original paper] shows the transient velocity of a single droplet at different coolant temperatures. As coolant temperature increases, the droplet' s acceleration period lengthens and its peak velocity also rises. This behavior is analogous to the effect of droplet temperature described earlier. When droplet temperature is fixed, higher coolant temperature allows water to reach boiling more readily, leading to prolonged evaporation time, higher evaporation rate, and greater total vapor volume. This promotes formation of a protective cavity that propels the droplet downward.

Fig. 8b presents the droplet expansion rate under different coolant temperatures. Although the duration of expansion rate growth lengthens with increasing

coolant temperature, the peak expansion rate decreases. At 20 °C, the droplet experiences unstable film boiling, where the vapor film collapses intermittently, causing repeated contact with water and fine fragmentation. As water temperature rises, heat transfer shifts toward stable film boiling, forming a persistent cavity that shields the droplet during descent until cooling. As a result, the expansion rate increases more gradually and the growth period becomes the longest. Fig. 8c shows representative phenomena and resulting debris at coolant temperatures of 20 °C, 50 °C, and 80 °C. With increasing coolant temperature, the droplet's leading edge becomes more rounded and resulting debris fragments become smoother. This occurs because more vapor is generated over the same period as coolant temperature rises, creating a more stable cavity that envelops the droplet, reduces direct water contact, and limits deformation. Peak pressure measurements obtained with a dynamic high-frequency pressure transducer further support these observations. As listed in Table 7 , peak pressure decreases with increasing coolant temperature. Finally, consistent with earlier findings, the moment of peak transient velocity coincides with that of the expansion rate.

Table 7. Peak Pressure at Different Water Temperatures

Time (ms)	Peak Pressure (MPa)
-	-

Fig. 9a [Figure 9: see original paper] shows the transient velocity of droplets for different materials. The lead-tin alloy droplet reaches the highest peak velocity upon entering water. This occurs because the alloy' s lower melting point allows it to store more internal energy at the same temperature. As a result, water evaporates more readily and a larger volume of vapor is generated, increasing the peak transient velocity of the droplet. Fig. 9b presents the expansion rate for each material. The lead-tin alloy and tin droplets exhibit significant fluctuations in expansion rate, whereas the lead droplet remains largely stable. This further suggests that, under identical conditions, lead is less susceptible to vapor explosion. Fig. 9c shows typical experimental phenomena and resulting debris for lead-tin alloy, tin, and lead. Owing to its higher melting point, lead has a lower degree of superheat at the same temperature, making it less prone to fine fragmentation. Peak pressure measurements support this observation, with values decreasing in the order: lead-tin alloy > tin > lead, as summarized in Table 8 . Consistent with earlier results, the moment of peak transient velocity coincides with that of the peak expansion rate.

Table 8. Peak Pressure at Different Droplet Materials

Time (ms)	Peak Pressure (MPa)
-	-

3.3 External Disturbance Pressure

The preceding analysis examined the laws governing transient velocity and expansion rate of droplets under self-triggering conditions. However, in actual severe accidents, various disturbances in the external environment can affect the droplet triggering process. This section introduces external disturbances by setting a disturbance plate in motion at the bottom of the water tank, focusing on the impact of external disturbance pressure, with specific conditions detailed in Table 4.

Fig. 10 [Figure 10: see original paper] illustrates the motion of a single droplet under Test D6, where the lead-tin alloy is initialized at 300 °C, the coolant is maintained at 20 °C, and the external disturbance pressure is 3 MPa. Before the lead-tin alloy droplet contacts the water surface, the water has already been perturbed by the external disturbance pressure, as reflected by bubbles moving upward in Fig. 10. Compared to Test A1, after the lead-tin alloy droplet enters the water surface, its penetration depth at the same moment is significantly reduced due to the action of external disturbance, and gas-liquid interface changes become more chaotic upon detachment from the water surface.

Fig. 11 [Figure 11: see original paper] shows the transient velocity of the droplet under different external disturbance pressures. With increasing external disturbance pressure, the duration of velocity increase after penetrating the water decreases, and the peak velocity of the droplet also decreases accordingly. The reason for this phenomenon is that after the droplet penetrates the water pool, drag force can rapidly decrease velocity. Meanwhile, with enhanced heat transfer at the interface, the hot droplet becomes surrounded by a thick layer of steam and air mixture, thus promoting drag reduction. This competition leads to velocity increase until peak velocity is reached. Moreover, when external disturbance pressure is introduced, the pressure may weaken the stability of the gas layer, thus increasing drag force. Therefore, with increasing external disturbance pressure, the peak pressure due to drag reduction decreases.

Fig. 12 [Figure 12: see original paper] shows the transient velocity comparison of lead-tin alloy droplets with and without external disturbance pressure at different droplet temperatures and water temperatures. The results also show that external disturbance pressure can reduce the peak velocity of droplets. Moreover, under external disturbance conditions, the initial temperature of droplets may have less effect on drag reduction, and external pressure dominates the settling process.

Fig. 13 [Figure 13: see original paper] shows the droplet expansion rate under different external disturbance pressures. As external disturbance pressure increases, the duration of expansion rate growth after the droplet enters water decreases; however, the peak expansion rate tends to increase. Even for lead droplets, the expansion rate can reach up to 9.46 m/s, as revealed in Fig. 13(c). The reason for this phenomenon is that as the droplet descends through water, initiation of trigger at the interface leads to fine-fragmentation in some local re-

gions. The resulting fine particles disperse around the parent droplet, forming a gaseous film that contributes to expansion of the hot droplets. When external disturbance pressure propagates, it readily induces increased instability of the droplet surface, thereby triggering further fine-fragmentation. Compared to the self-trigger scenario, this localized fine-fragmentation process is more pronounced. Consequently, as external disturbance pressure increases, the droplet expansion rate correspondingly escalates. Moreover, the cavity is more likely to collapse under external disturbance pressure, which accelerates contact time between the droplet and water, thereby increasing the degree of fine-fragmentation, as shown in Fig. 14 [Figure 14: see original paper].

Fig. 15 [Figure 15: see original paper] shows the comparison of expansion rate of lead-tin alloy droplets with and without external disturbance pressure at different droplet temperatures and water temperatures. The results also show that external disturbance pressure can reduce the rise time of the droplet expansion rate and increase its peak value. In addition, with increasing initial droplet temperature or coolant temperature, external disturbance pressure can further promote the triggering process, with the highest growth rate reaching 108% when coolant temperature is around 80 °C. Therefore, particular attention should be paid in severe accident scenarios close to saturation conditions, where external triggers may occur.

Fig. 16 [Figure 16: see original paper] shows the mass ratio of product fragments with diameter less than 0.5 mm under different working conditions. With increasing external disturbance pressure, the mass ratio of product fragments with diameter less than 0.5 mm also increases. At the same time, peak pressure measured by the dynamic high-frequency pressure transmitter in the experiment can also illustrate this phenomenon, as shown in Table 9 . With elevation of external disturbance pressure, peak pressure values manifest an ascending trend. Conversely, as coolant temperature increases, peak pressure values exhibit a descending trend. Furthermore, an increase in droplet temperature is associated with a biphasic trend in peak pressure values, initially increasing and subsequently decreasing. Ultimately, comparative analysis of transient velocity and expansion rate moments reveals that the peak transient velocity moment is synchronized with the peak expansion rate moment.

Table 9. Peak Pressure Under Different Working Conditions

Time (ms)	Peak Pressure (MPa)
-	-

Another important point to address is that the primary factor influencing measured pressure variation is the distance between the measuring point and the molten droplet. As pressure propagates from the local triggering region, it attenuates due to water resistance. The pressure decay can be estimated using Eq. (8):

$$P = P_0 r^{-b}$$

where P and P_0 refer to the triggering pressure at the measuring point and at the surface of the molten droplet, respectively; r refers to the distance between the measuring point and the location of the molten droplet at the triggering time; and b refers to the empirical coefficient, usually regarded as 1.03 in water. Using this equation, the corresponding peak pressure at the droplet surface can be effectively reconstructed. For instance, in Test A3 and Test D3, the measured triggering pressures were 0.022 MPa and 0.081 MPa, respectively. Applying the correction, the estimated pressures at the droplet surface are approximately 0.57 MPa and 2.1 MPa. These results demonstrate that the applied external disturbance significantly enhances trigger pressure compared to spontaneous triggering conditions.

3.4 Comparison with Previous Work and Limitations of the Present Study

A recent study by KTH in Sweden [47] examined steam explosion characteristics involving multiple molten tin droplets falling through a coolant pool. This configuration is highly similar to the present work, in which streams of molten Sn, Pb, and Sn-Pb alloy droplets descend through a coolant pool. The authors reported distinct and complex steam explosion behaviors not observed in earlier single-droplet experiments—an important finding, given the limited available data on multi-droplet configurations and the clear need for deeper investigation into such conditions. In their tests, a spontaneous steam explosion was initiated, and triggered explosions were speculated to occur subsequently, though the underlying mechanism remains unclear. In the present study, by applying external disturbance pressure in direct contact with the molten droplets, external triggering is reliably achieved. Notably, even lead—a material known for its resistance to explosion—could be triggered under 3 MPa external disturbance, generating a peak pressure of 64 kPa.

It should also be noted that, due to the relatively similar mass of Sn droplets used in the experiments, peak pressures ranging from 1 to 33 kPa (as shown in Fig. 17 [Figure 17: see original paper]) were obtained across different initial melt masses. In the present study, Sn was used in cases C1, D8, D9, and D10. For the internally triggered case, a peak pressure of 19 kPa was recorded, while externally triggered cases yielded peak pressures of 26 kPa, 49 kPa, and 74 kPa —values that align reasonably well with earlier experimental results from KTH.

In summary, this study focused primarily on the triggering behavior of small-scale molten droplets at temperatures up to 800 °C, a range compatible with high-speed visualization. However, evidence [40] suggests that higher-melting-point materials may undergo significantly different fuel-coolant interactions, potentially altering steam explosion strength. Moreover, the explosion behavior of such materials under external triggering remains complex and inadequately

understood. Additionally, due to obscuration by the vapor envelope, the droplet-gas interface could not be clearly resolved with high-speed imaging. As a result, expansion rates could only be estimated approximately from the extent of the gas phase. X-ray imaging appears to be a promising alternative for tracking internal structures during FCI, especially for high-melting-point materials. As such materials cool, rapid crust formation [12] may influence the interaction more strongly than external triggers. Understanding how these mechanisms compete and interact will be a key focus of our subsequent research.

4. Conclusion

This study investigated the behavior of molten droplets during fuel-coolant interactions under external disturbance conditions using a self-designed FCI experimental facility. The transient velocity, expansion rate, dynamic phenomena, debris characteristics, and peak pressures under various conditions were analyzed in detail. The main findings are as follows:

1. Analysis of droplet transient velocity reveals that cavity formation reduces droplet resistance, leading to increased peak velocity. In the absence of external disturbance, higher droplet and coolant temperatures promote faster and more stable cavity formation, resulting in a rising trend in peak droplet velocity. Under external disturbance, however, increased disturbance pressure makes the cavity more prone to collapse, and peak droplet velocity decreases accordingly.

2. Evaluation of droplet expansion rate shows that, without external disturbance, the peak expansion rate initially increases and then decreases with rising droplet temperature, while it decreases with increasing coolant temperature. Under external disturbance, the peak expansion rate increases with disturbance pressure. At 3 MPa external pressure, the peak expansion rate more than doubles.

3. Based on trigger pressure peaks and debris morphology, external disturbance appears to shorten the triggering time of the droplet surface and enhance triggering intensity. This requires particular attention in severe accident scenarios close to saturation conditions, where external triggers may occur.

The present study serves as the first part of a broader investigation into the effect of external disturbance on molten droplet triggering. Newly observed phenomena—such as air entrainment and its influence, as well as the interplay between vapor-induced drag reduction and external disturbance—will be further examined through theoretical modeling. The current data on peak velocity, expansion rate, and peak pressure provide a valuable database for validating subsequent theoretical or numerical models. Incorporating these phenomena into simulation codes such as MC3D or SIMMER will improve interpretation of FCI processes and help reduce predictive uncertainties.

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