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Modelling Approach for Premixing Phase in Combination of Melt Jet Breakup and Premixed Layer Formation of Melt Spread

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ABSTRACT

A vapour explosion is a possible threatening consequence of a fuel-coolant interaction. This phenomenon can occur during a severe accident in a nuclear power plant, when the molten reactor core may come in contact with the coolant.

An intertwined melt-jet coolant pool and stratified configuration is a realistic condition. However, past research was devoted to either melt-jet coolant pool configuration or stratified configuration and thus an important uncertainty regarding vapour explosion assessment raised.

First objective is to analyse the vapour explosion experiments in combined stratified and melt jet configurations to improve the understanding of fuel-coolant interaction. Secondly, modelling of melt-coolant mixing prior to vapour explosions, which largely defines the amount of melt, participating in the vapour explosions, is being studied.

The developed modelling approach, based on the evaluation of the models for the individual phenomenon enables the estimation of the premixing phase in combination of melt jet breakup and premixed layer formation of melt spread, which is of high importance in nuclear safety.

1 INTRODUCTION

During a hypothetical severe accident in a light water nuclear power plant, the molten reactor core may come in contact with the coolant water [1]. The interaction between them is known as a fuel-coolant interaction (FCI). One of the consequences can be a rapid transfer of a significant part of the molten corium thermal energy to the coolant in a time scale smaller than the characteristic time of the pressure relief of the created and expanding vapour. Such a phenomenon is known as a vapour explosion [1,2]. The process can escalate as part of the released mechanical energy enhances further fine fragmentation of the melt leading to more rapid heat transfer from the melt to the coolant. Given the possibly large amount of thermal energy, initially stored in the liquid corium melt at about 3000 K, that can potentially result in pressure peaks of the order of 100 MPa, vapour explosion can be a credible threat to the structures, systems and components inside the reactor containment. It can also threaten the integrity of the reactor containment itself, which would lead to the release of radioactive material into the environment and threaten the general public safety.

The vapour explosion is commonly divided into the premixing and the explosion phase. The premixing phase covers the interaction of melt with coolant prior to vapour explosion. During this time, the continuous melt is fragmented into melt drops the size of a couple of millimetres. The melt drops and the coolant are mixed due to the density and velocity differences and also due to vapour production. If a vapour film destabilization occurs in such a system, the phenomenon is continued into a vapour explosion. The process can escalate as part of the released mechanical energy enhances further fine fragmentation of the melt leading to more rapid heat transfer from the melt to the coolant.

An important condition for the possible occurrence of strong, energetic vapour explosion and the self-sustained process of shock wave propagation is the existence of a so-called premixture of fragmented melt and coolant. In nuclear reactor safety analyses vapour explosions are primarily considered in the melt jet configuration where sufficiently deep coolant pool conditions provide complete jet breakup and efficient premixture formation. On the other hand, stratified melt-coolant configurations, i.e. a molten corium layer below a coolant layer, were only recently recognized as being able to generate strong explosive interactions [3,4]. Our recent research [4] was devoted to understanding FCI in stratified configuration, especially to premixed layer formation – mixture of coolant and melt drops, ejected from the melt. Namely, the previously performed experiments in the PULiMS facility (KTH, Sweden, Figure 1) with high melting temperature oxidic simulants of corium revealed that strong vapour explosions may develop spontaneously in what was considered as a stratified melt-coolant configuration [3,5].

Despite extensive research work, large uncertainties remain and reflect the lack of detailed understanding of the FCI processes. Recently, an important safety-related uncertainty was revealed, related to the prediction of vapour explosion strength in combined stratified and melt jet configurations [6].

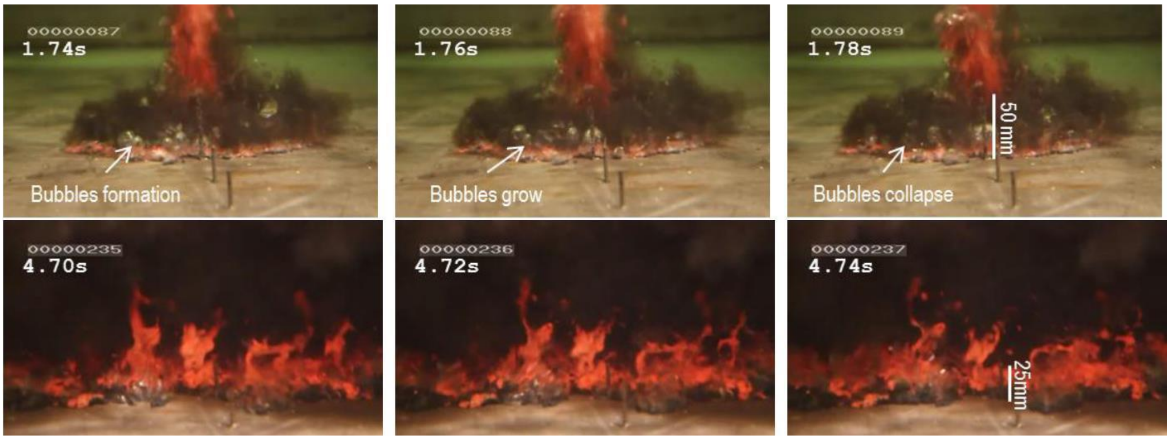

Figure 1: Melt jet and melt spreading with the formation of the premixed layer in the PULiMS-E4 experiment. The figure is adopted from [5]

The observed uncertainty and lack of understanding of FCI in combined stratified and melt jet configurations have an important impact on the safety-related issue of FCI in nuclear power plants, because:

- The amount of melt in combined stratified and melt jet configurations available to participate in the explosion can be much larger than assessed before due to combined contributions of premixed layer formation in stratified melt-coolant configuration and breakup of melt jet;

- The combined stratified and melt jet configuration presents a realistic condition in e.g. nuclear power plant severe accident when the reactor cavity is only partially flooded. The possible strong vapour explosions may present an increased threat.

The objective of the paper is to analyse the possibility of modelling the melt-coolant mixing in combined stratified and melt jet configurations prior to vapour explosions, which largely defines the amount of melt, participating in the vapour explosions. Modelling, based also on the evaluation of the models for the individual phenomenon, improves the understanding of FCI.

The overview of the state-of-the-art modelling approaches enables the estimation of the premixing phase in combination of melt jet breakup and premixed layer formation of melt spread, which is of high importance in nuclear safety.

2 EXPERIMENTAL REVIEW

Some past experimental work can be identified as an FCI in combined stratified and melt jet configuration. When the melt was poured in a shallow pool of coolant, the geometry of our interest could be achieved. Two recent experiments PULiMS, SES [3,7] were primarily devoted to melt spreading under water and FCI in stratified melt coolant configuration. However, in both cases, the melt was pored as a jet in a shallow pool of water. In both cases, a combined stratified and melt jet configuration was achieved during the melt pouring and at the time of the vapour explosion. Both experiments are described in more details in sections 2.1 and 2.2.

Many other experiments can be considered relevant for investigation of partial phenomenon. More than 30 tests in a deep pool (0.6 – 1.5 m) configuration were performed in the DEFOR facility (KTH, Sweden). The configuration was fragmented melt jet – coolant pool. The same materials were used as later in the PULiMS and SES experiments. The melt was superheated up to 320 K and the water subcooled (10 - 30 K). The ratio between the pool depth to the jet diameter was large (~ 25 - 50) [5]. Temperatures of the melt, water subcooling and jet diameter were similar to the PULiMS tests. They did not result in spontaneous vapour explosion. The main difference was a deeper water pool in the DEFOR experiment.

In the experiment by Board and Hall (Berkeley Nuclear Laboratories, USA), collapse of a vapour film and propagation of a vapour explosion in stratified configuration were studied [8]. Three series of tests were carried out. The first one was devoted to study the collapse of the vapour film caused by a sudden variation of the ambient pressure. Tin was poured into a shallow crucible placed under water. The interaction was triggered, when all the tin was already poured, representing only a stratified configuration. In the other two series the propagation of the explosion along the hot liquid - cold liquid interface with two different confinements was studied. Tin was poured into narrow long tank, submerged in water. Only in one case, a spontaneous interaction occurred near one end, not being clear whether the configuration was still combination of stratified and melt jet configuration. In other cases, the interaction was triggered after the pouring, representing only a stratified configuration.

The formation of debris as the result of FCI (energetic or not) has been studied experimentally in the FARO and KROTOS facilities at JRC-Ispra [9]. The FARO tests were designed to study the integral corium melt jet/water mixing and quenching behaviour. In the FARO experiment [10], the presence of a cake at the bottom was interpreted as an incomplete breakup of the melt jet before reaching the bottom, i.e. that the melt breakup length was larger than the water pool depth. This suggest a combined stratified and melt jet configuration. However, in the described FARO experimental tests, all of them performed in saturated water, no vapour explosions occurred.

The KROTOS vapour explosion experiments revealed important differences in tendency for spontaneous triggering of explosion, energy conversion efficiency and melt jet breakup characteristics between the corium and alumina melts [11]. Tests were performed in a test vessel that allowed direct visual observations of melt injection and mixing conditions. The melt was injected into a 1 m deep subcooled water pool, but no evidences of a combined configuration was presented [12]. The data from the thermocouples show that a coherent corium melt pour tends to penetrate deeper into the water pool than an alumina pour. In some cases, also spontaneous vapour explosions occurred.

It can be concluded, that although scarce, the combined stratified and melt jet configuration was the case in some of the past experiments related to the FCI research. Usually, the emphasis was not on this combined configuration and if the explosion was observed, it was not analysed in details regarding different contributions. Analysis of premixed layer in stratified configuration and it's contribution to an explosion was done as a part of our previous research [4]. It was concluded that for more realistic explosion strength assessment, additional contributions should be included in the modelling. This can be confirmed also by the experiments as intertwined phenomena of FCI prior to an explosion can be observed in some cases.

2.1 PULiMS experiment

The Pouring and Underwater Liquid Melt Spreading (PULiMS) experiment (KTH, Sweden) was devoted to the melt spreading observation [3]. The test section consisted of an induction heated furnace for melt heating, a funnel through which the melt was poured and a bottom container of 2 m × 1 m × 1 m with a 10 mm thick bottom steel plate. The container was partially filled with water in which the melt was released and then spread on the bottom [5]. During the melt release, a combined stratified and melt jet configuration was achieved.

Tests were primarily devoted to the melt spreading under the water. Post-test inspection included detailed investigation of the debris and cake structure. However, unexpectedly some spontaneous strong vapour explosions occurred during some of the tests. Vapour explosion destroyed the facility and made the observation of melt spreading more difficult. The solid melt cake, inspected after the tests, usually consisted of a 2–3 mm thick solid bottom layer with low porosity, a 1–2 cm thick porous intermediate layer including large cavities and a top crust layer with large fraction of enclosed cavities. On top of the cake, volcanic-like structures were found, which were said to originate from the eruptions of melt through the melt crust [5]. The far edge of the cake bottom was typically lifted upwards for a few millimetres.

Contrary to the most of the previous experiments, the phenomena during the melt spreading was also recorded. FCI of melt and water was clearly observed. During the initial stage of melt spreading, a formation, growth and collapse of the vapour bubbles in the subcooled water was observed [5], as seen in Figure 1. When the melt spread further, creating a larger pool of melt beneath the water, more energetic interaction was observed with some melt ejections reaching around 10 cm in height, as seen in Figure 1.

The amplitude of interface instabilities was increasing with time and in some of the tests, a spontaneous vapour explosion or more of them occurred. The peak in the interface instabilities was observed right prior to the explosion [5]. These instabilities created the so-called premixed layer. In the premixed layer, as said by Konovalenko et al. [5], strong vapour explosion can be triggered.

2.2 SES experiment

As a successor of the PULiMS experiment, the Steam Explosion in Stratified melt-coolant configuration (SES) experiment (KTH, Sweden) was performed [3]. The experiment was designed to study vapour explosions in the stratified configurations and the effect of initial conditions on the strength of vapour explosion.

The test section was similar to the one in the PULiMS experiment. Melt was generated in the furnace, then released through the funnel in the shallow pool of water. The size of the steel container was about half of the one in the PULiMS experiment (1 m × 1 m and 0.8 m in height). The whole frame of the test section was set on the dynamic sensors to record the force and impulse of the explosions. Phenomena were recorded by high-speed cameras and by thermocouples inside the test section.

In the E series of tests, 3 tests were performed. In all of them ZrO_2-WO_3 was used. In the E1 and E2 tests, the funnel nozzle with diameter of 20 mm was used, placed 200 mm above the water level and 200 mm of water was in the pool. In the E3 test, diameter of the nozzle was 30 mm, placed only 50 mm above the water and 220 mm of water was in the pool. During the melt release, a combined stratified and melt jet configuration was achieved.

In the tests, growth and collapse of large vapour bubbles were observed and spontaneous vapour explosions occurred at different times. In the E1 and E2 tests also secondary explosion was observed, but were weaker. It was reported that in the E series of tests, the weakest explosion was in the E2 test with subcooling of water for 14 K. In the E3 test with water subcooling of only 5 K, no explosion was observed. In the E3 test, a 30–60 mm thick vapour layer covered the melt while in the other tests individual vapour bubbles were observed.

In the next series of SES tests, the S1 test was performed in the frame of the SAFEST project (Severe Accident Facilities for European Safety Targets) [7]. The proposal for the test was made in collaboration by an international team being led by EDF (France) and JSI. The main aim of the test was to exclude the melt jet fragmentation in the water pool before melt spreading on the bottom plate of the test section. Therefore, the nozzle for the melt release was positioned just 30 mm above the bottom plate, inside the water. Compared to the previous SES tests, different material, Bi_2O_3-WO_3 was used. It has lower melting point as previously used ZrO_2-WO_3. Therefore, it produces less light emissions. The negative side of this material is larger dust production. In the S1 test, a water pool depth of 25 cm was used. During the melt pouring, strong fragmentation of melt was observed. The S1 test resulted in a vapour explosion just 0.6 s after the melt release. Already prior to this explosion, smaller explosion occurred. De Malmazet et al. [7] connected this small explosion with the initial impact of melt on the test section bottom steel plate. Explosion damaged the melt delivery system, which affect the later melt pouring and consequently the melt cake and melt debris distribution.

3 MODELING OF COMBINED STRATIFIED AND MELT JET CONFIGURATION

Past research was devoted to either melt jet configuration, where the melt jet penetrates into a deep pool of coolant, or stratified configuration, where the melt is spread below the coolant. However, an intertwined configuration can be a realistic condition, as seen also from some experiments. If the melt is poured into the coolant pool and the coolant pool is not deep enough to provide the complete melt jet breakup, the remaining melt jet reaches the bottom and spreads. In this case, a combination of stratified and melt jet configuration can be created.

As found out, considering only the stratified configuration of spread melt under the water layer and its contribution to the mixing significantly underestimates the assessed explosion strength. In the PULiMS experiment, the melt jet, falling through the shallow, 20 cm deep pool of water created also additional mixing of melt and coolant and created a combined stratified and melt jet configuration [4].

Below, the individual phenomenon modelling is presented, combination of which can be used for the modelling of the combined phenomena.

3.1 Melt jet breakup

During a melt jet breakup, multiple phenomena occur simultaneously [13]. Interfacial instabilities, liquid entrainment and stripping from the interface are hydrodynamic interactions while the thermal interactions are coolant boiling and solidification of the melt surface. Jet breakup is characterized by the melt jet breakup length and melt jet breakup mode [14].

Two correlations are generally used for the melt jet breakup length. The Epstein and Fauske model (Eq. 1) [15] depends on the material properties (index j and c stand for jet and coolant, respectively) and jet diameter (Dj), with E_0 being the so-called entrainment coefficient:

$$\frac{L_{brk}}{D_j} = \frac{1}{2E_0}\sqrt{\frac{\rho_j}{\rho_c}} \,. \tag{1}$$

More widely used is the correlation by Saito (Eq. 2 and Figure 2) [16], which depends on the material properties, velocity of the melt jet (Fr is a Froude number) and its diameter:

$$\frac{L_{brk}}{D_j} = 2.1\sqrt{\frac{\rho_j}{\rho_c}} \cdot \sqrt{Fr} \,, \tag{2}$$

$$Fr = \frac{v^2}{gD_j} \,. \tag{3}$$

The melt jet breakup length cases with impact velocities of 1m/s and 10 m/s (which are typical values, based on the experimental observations) are shown in Figure 2.

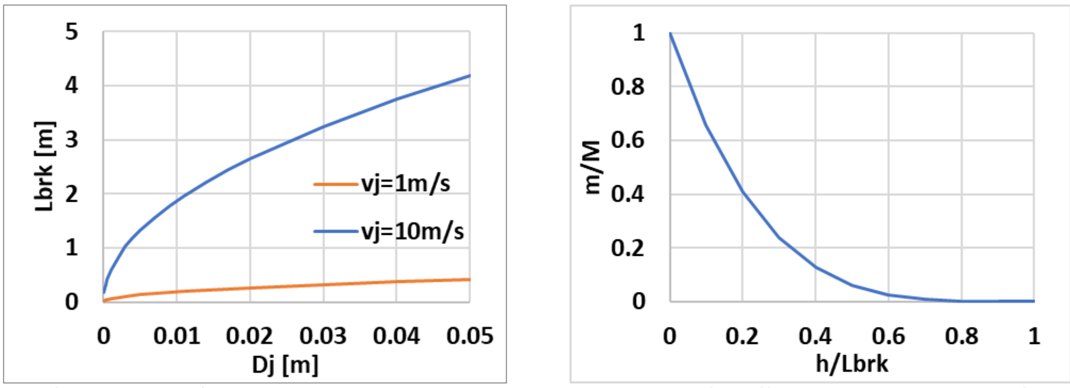

Figure 2: Left: Illustration of the melt jet breakup length L_{brk} with Saito correlation for different melt jet diameters D_j for arbitrary melt jet impact velocities v_j (with material properties ρ_j = 7800 kg/m^3, ρ_c = 1000 kg/m^3,). Right: Amount of the initial melt jet which does not undergo breakup at a certain depth h of water compared to the melt jet breakup length L_{brk}.

For the melt jet breakup mode, the initial transient of the melt jet penetration into coolant is usually related to Rayleigh-Taylor instability, while the Kelvin-Helmholtz instability is considered for the quasi-steady regime of melt jet breakup [14]. With those models, fragmentation and melt drop size are determined according to the local conditions. Possible further breakup of the melt drops is usually modelled with consideration of the critical Weber number.

3.2 Melt pool fragmentation

If the melt jet breakup is not complete, the remaining melt reaches the bottom and spreads out, creating a melt pool. The amount of melt, which does not undergo melt jet breakup can be assessed based on the breakup length, e.g. the Saito correlation, and the depth of the water pool (Figure 2). The melt jet reaching the bottom of the test section and spreading out was clearly observed e.g. in the PULiMS experiments (Figure 1) and some other experiments [9].

The melt spreading was experimentally studied, e.g. at facilities BNL (USA), SPREAD (Japan), CORINE (France), VULCANO (France), KATS (Germany), COMAS (Germany), ISPRA (EU JRC), S3E (Sweden) [17]. Currently, from 2019 to 2024, the OECD ROSAU (Reduction Of Severe Accident Uncertainties) programme is aiming to reduce knowledge gaps and uncertainties associated with severe accident progression. Two main research areas are the spreading of melt in a cavity and in-core and the ex-core debris coolability with planned experiments at the Argonne National Laboratory (USA) with up to 300 kg of molten prototypical corium material at temperatures up to 2400 °C.

As discussed by Dinh et al. [17], who were studying melt spreading at the macroscopic scale, melt spreading can be described as a hydrodynamic process. The spreading is governed by the gravitational, inertial and viscous forces. It can be divided into the gravity-viscous regime, in which viscosity plays a dominant role, while in the gravity-inertia regime, the influence of the melt viscosity may be neglected. The surface tension has an effect only for very low velocities of melt spreading. When the melt is spreading under a coolant, their interactions may influence the spreading as well [17].

The melt spreading can be terminated by melt solidification. The melt solidification during the spreading is affected by heat transfer from the melt to the structures and coolant, possible heat generation and the melt solidification behaviour [17].

The melt-coolant interaction of the melt pool under the layer of coolant is described by the model for premixed layer formation in stratified fuel-coolant configuration [4]. In geometry with a continuous layer of melt under a layer of water, called stratified configuration, the melt is usually hot enough for the coolant to vaporize. Due to the instabilities, the bubbles arise from the vapour film. In subcooled water, bubbles condense and collapse. During the asymmetric bubble collapse, water at the bubble interface accelerates towards the melt surface, creating a so-called coolant micro-jet. The pressure perturbations on the melt surface, usually due to the vaporization of the coolant micro-jets can produce the melt surface instabilities and fragmentation of the melt. This phenomenon is the so-called premixed layer formation of melt drops in the coolant layer above the melt pool. The model describes the premixed layer formation with three key characteristics, i.e. size of ejected melt drops, their initial velocity and the fragmentation rate of the continuous melt phase [5].

4 DISCUSSION AND CONCLUSIONS

Using only the model for the premixed layer formation in stratified configuration for the experiments in at least partially combined configuration of melt jet and underwater melt pool underestimates the strength of the produced vapour explosions. The possible explanation is an inadequate amount of premixing in the simulations due to considering only one contribution [4].

This highlights the need for more complex modelling of FCI in combined configuration of melt jet and underwater melt pool. Till now FCI models focused either on the melt jet configuration or on the melt pool configuration, but these models were never coupled. In our modelling approach, we are trying to couple both models, thus being able to adequately consider intertwined melt-jet coolant pool and stratified configurations, which are realistic conditions.

During the melt jet breakup, multiple phenomena occur simultaneously, creating a mixture of fragmented melt jet and coolant. The melt jet breakup length indicates how much jet has been broken up at a certain coolant depth and whether there is a possibility for the combined configuration. The melt jet breakup mode describes the produced fragments.

The unfragmented melt jet reaches the bottom and spreads out. Based on the previous analysis of FCI in a stratified configuration only, a large effect on the strength of the potential vapour explosion has the surface area of the melt pool. Therefore, the accurate assessment of the spread melt is of high importance for the reliable assessment of the contribution of the premixed layer above the melt pool to the total premixing.

Only considering both the above contributions for the premixing could result in a more reliable assessment of vapour explosions in combined configuration of melt jet and underwater melt pool. However, the FCI phenomena are in general very complex. A more precise calculation of a vapour explosion, which is of high significance for nuclear safety, would be possible only by using dedicated computer codes.

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