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Study on thermal fragmentation characteristics of a superheated alumina droplet

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ABSTRACT

In the frame of the European Commission FP7 SAFEST project, IRSN proposed to experimentally investigate the steam explosion triggering mechanisms of a superheated alumina droplet falling into water, through a set of experiments in the Micro Interactions in Steam Explosion Energetics facility (MISTEE) at KTH. Since thermal fragmentation is considered to be a likely process for the triggering of Steam Explosions in the KROTOS tests (performed at CEA) with alumina, the ability of a single droplet of such material to undergo thermally induced fine fragmentation is studied on the MISTEE facility with a close-up visualization.

A series of experiments were conducted, where droplets of molten alumina were discharged into a water pool and potentially exposed to a small pressure wave. The intense interactions were recorded with a high-speed camera along with the pressure in the droplet vicinity.

The ability of alumina to undergo thermal fragmentation is expected to be firstly contingent on the stability of the vapour film enshrouding the melt droplet. The water and melt temperatures may then play a crucial role on the vapour film stability, and therefore on the observation of a steam explosion. Indeed, under high to moderate water sub-cooling conditions, experimental observations indicate that fine fragmentation of the melt can occur when the droplet is exposed to even a weak pressure wave, in the range of 0.15 MPa. In contrast, melt fine fragmentation is suppressed at low water sub-cooling conditions (less than 30 °C), where the formation of a thick vapour film (and large wake) is observed, and which is probably too stable to be destabilized by the weak pressure wave.

The effect of the melt temperature on thermal fragmentation is also assessed. This parameter influences the solidification of the droplet and the strength of the explosion as it determines the available heat energy. In the present conditions, fine fragmentation of melt occurred even at quite low melt superheat (≈60 °C). For a high melt superheat (above 200 °C) a very energetic spontaneous steam explosion was observed. A physical analysis on the debris particles acquired indicates a mass median diameter of ≈100 μm, comparable to the one observed in the KROTOS alumina experiments.

The MISTEE experimental results are finally used to assess the heat and mass transfer modelling of the coolant during the fragmentation process in the FCI code MC3D.

1. Introduction

A severe nuclear accident can involve high temperature molten materials, including the nuclear fuel, called corium, poured into the coolant fluid. The mixing process that then occurs between the two is generally called FCI (Fuel-Coolant Interaction). FCI may involve two steps. In the first one, the mixing occurs quite quiescently, involving melt fragmentation at the scale of some millimetres. Under some conditions, this pre-mixing phase can be interrupted by a strong explosion, called steam explosion, where the thermal energy is transformed massively into mechanical energy, due to a very fine fragmentation process of the melt. This type of very energetic phenomenon leads to the formation of shock waves and can endanger the structures and the containment of the radioactive materials. The explosion phase happens when the pressure build-up due to both the void production and the coolant properties modifications caused by the temperature increase is faster than the time needed for the system to release the pressure. State-of-the-art reviews on experimental and analytical studies of steam explosion can be found in (Corradini et al., 1988; Fletcher, 1995; Meignen et al., 2014; Meignen et al., 2014; Meignen et al., 2014).

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The steam explosion is initiated locally by some triggering events that are still not very well known and understood. Several mechanisms have been identified and studied, among which, the so-called thermal fragmentation. This specific phenomenon leads to the fast fragmentation (within some milliseconds) of a hot liquid droplet into fine fragments while under stable hydrodynamic conditions (i.e. low Weber number). The fragmentation occurs generally in 2 or 3 steps, in an apparent isotropic way. Several hypotheses have again been made to explain this specific phenomenon and the analyses have eventually converged towards a mechanism first proposed and modelled by Kim and Corradini (1988). The authors postulated that, under a destabilization of the vapour film through a Rayleigh-Taylor mechanism, small jets of coolant could penetrate the droplet, vaporize and induce the fragmentation. A thorough analysis of thermal fragmentation is given by Lamome and Meignen (2008), based on the experimental results and studies made by Nelson and Duda (1981, 1985). Lamome and Meignen (2008) indicated that the phenomenon in fact could be initiated, for a hot droplet initially enshrouded in a vapour film, by local quasi liquid-liquid contacts (the real contact being thermodynamically impossible) between the hot material and the coolant. These contacts would lead to very high local heat and mass transfers and pressurizations, and consequently, through again a Rayleigh-Taylor mechanism, to instabilities of the interface and then fragmentation. The precise development of the fragmentation is nevertheless still partially known as it is clear that analytical modelling reaches rapidly some limits, whereas more direct numerical investigation is still out of reach.

The MISTEE facility at KTH allows studying the thermal fragmentation of a single hot droplet of molten material falling into water in the film boiling regime. A small pressure wave (around 1 or 2 bars) can be applied to the droplet in order to destabilize the vapour film and trigger the thermal fragmentation. Experiments within MISTEE have been made for several kinds of materials with relatively low melting temperature such as tin (Park et al., 2005; Hansson et al., 2009) or the binary oxide WO_3-CaO (Hansson et al., 2013). Typically, during the thermal fragmentation, between two and three cycles of expansion and collapse of a vapour bubble around the droplet are observed, indicating two to three cycles of fragmentation. These observations are in accordance with Nelson and Duda (1981, 1985) findings with iron oxide. However, X-ray measurements in MISTEE indicated that the droplet fragmentation occurs during the second and third cycles (Park et al., 2005).

Within the framework of nuclear power plant safety R&D, a number of steam explosion experiments have been conducted with various corium simulant and prototypic materials to understand the thermal-hydraulic processes that govern the explosivity. In the KROTOS experiments at CEA, spontaneous steam explosions were observed with alumina (Al_2O_3), while no explosion occurred with prototypic corium in similar conditions (Huhtiniemi et al., 1999). It is now largely admitted that the large loads observed with alumina are mainly due to its low density which generates large droplets and thus low void and slow solidification. Concerning the void, for a sub-cooling of around 80 °C, a void fraction around 2% with alumina is reported in (Huhtiniemi et al., 1999) while it is approximately 10 times bigger with corium. As for the solidification, although no specific measurement of the solidification rate has been made, the solidification effect is admitted to be negligible during the course of the KROTOS experiments, as shown in (Uršič et al., 2012). Still, there are several other questions related to this material effect that are not answered yet, in particular the triggering mechanism, and that can be addressed with MISTEE. In the frame of the SAFEST European Commission FP7 project (http://cordis.europa.eu/project/rcn/188519_en.html), the ability of alumina to undergo thermal fragmentation has thus been studied in the MISTEE facility. The melting temperature of alumina is significantly higher (around 2054 °C as given in (Schneider, 1979) than the range of temperatures previously used in MISTEE (see (Park et al., 2005; Hansson et al., 2009; Hansson et al., 2013) and the facility was accordingly upgraded. This series of experiments is thus also a first step toward the study of real corium in the MISTEE facility.

The experimental facility and the performed experiments are first presented. The ability of alumina to undergo thermal fragmentation is evidenced. The effect of the water sub-cooling on the explosivity is then studied and the stabilizing role of the vapour film is highlighted. As the melt superheat can also be expected to impact the results, since it modifies the time when the solidification occurs, the effect of this parameter is also analysed. The last section presents briefly a numerical analysis performed with the MC3D code (Berthoud and Valette, 1994). This study allows a first detailed interpretation of the development of the explosion, as well as a validation, in realistic conditions, of the heat and mass transfer models used in the code.

2. Experimental measurements

2.1. MISTEE facility

The MISTEE facility is presented on Fig. 1. Its main elements are the melting chamber, the confined water pool chamber, the external triggering system and the fast synchronous visual acquisition system. The melting chamber, where approximately 1 g of solid alumina with 99.8% purity is initially placed, is a high frequency induction furnace (20 kW, 50–250 kHz) and is located at the top of the experimental installation. It is detailed on the right of Fig. 1. In order to melt alumina and study the effect of different melt superheat, temperatures typically up to 2300 °C must be reached. Concentric tubes of advanced ceramics (porous zirconia, alumina and magnesia) surround the tungsten crucible to minimize heat losses. The crucible temperature is monitored by the use of a C-type tungsten rhenium thermocouple mounted from the side of the crucible.

The melt prepared in the tungsten crucible is aerodynamically plugged by a constant purge of inert gas through the 5 mm crucible nozzle. A fast acting three-way valve is used to control open/close operation for gas flow through the nozzle and also to isolate the furnace from the water pool chamber. When the desired temperature is achieved in the crucible, the fast acting three-way valve is released thereby discharging the melt droplet into the water pool chamber. The droplet temperature before entering the water pool is also monitored by a fast two-colour (i.e. emissivity compensated) pyrometer with a spectral range between 1.4 and 1.8 μm and uncertainties on the temperature measurements around 12 °C (Pyrometer on Fig. 1.

The water pool chamber is a rectangular plexi-glass tank of dimensions 180 mm * 130 mm * 350 mm. K-type thermocouples are used to monitor water temperature at two levels (TC on Fig. 1).

During the experiments, destabilization of the vapour film and the subsequent (quasi) melt-water contact is initiated by an external triggering system. It is a piston set-up located at the bottom of the water pool chamber. The piston set-up is driven by the rapid discharge of a capacitor bank made of three capacitors of 400 Vdc and 4700 mF each. The triggering system generates a sharp pressure pulse of up to 0.15 MPa with a rising time of 50 μs. Two pressure transducers have been added to the facility to measure the pressure at the top of the water tank and near the area where the pressure wave hits the droplet (noted PT on Fig. 1). One of the transducers being located near the interaction location, it is assumed that the pressure recorded at this point approximates the pressure seen by the droplet. This triggering pressure is known