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Simulation of steam explosion in stratified melt-coolant configuration

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HIGHLIGHTS

- Strong steam explosions may develop spontaneously in stratified configurations.
- Considerable melt-coolant premixed layer formed in subcooled water with hot melts.
- Analysis with MC3D code provided insight into stratified steam explosion phenomenon.
- Up to 25% of poured melt was mixed with water and available for steam explosion.
- Better instrumented experiments needed to determine dominant mixing process.

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ABSTRACT

A steam explosion is an energetic fuel coolant interaction process, which may occur during a severe reactor accident when the molten core comes into contact with the coolant water. In nuclear reactor safety analyses steam explosions are primarily considered in melt jet-coolant pool configurations where sufficiently deep coolant pool conditions provide complete jet breakup and efficient premixture formation. Stratified melt-coolant configurations, i.e. a molten melt layer below a coolant layer, were up to now believed as being unable to generate strong explosive interactions. Based on the hypothesis that there are no interfacial instabilities in a stratified configuration it was assumed that the amount of melt in the premixture is insufficient to produce strong explosions. However, the recently performed experiments in the PULiMS and SES (KTH, Sweden) facilities with oxidic corium simulants revealed that strong steam explosions may develop spontaneously also in stratified melt-coolant configurations, where with high temperature melts and subcooled water conditions a considerable melt-coolant premixed layer is formed.

In the article, the performed study of steam explosions in a stratified melt-coolant configuration in PULiMS like conditions is presented. The goal of this analytical work is to supplement the experimental activities within the PULiMS research program by addressing the key questions, especially regarding the explosivity of the formed premixed layer and the mechanisms responsible for the melt-water mixing. To better understand these phenomena a comprehensive parametric analysis was performed with the MC3D code, varying the premixed layer melt fraction, void fraction, and thickness, the melt spreading area, the melt droplet size, the water height, the water subcooling and the trigger strength. The results are discussed and compared to available experimental data. It seems that both identified melt-water mixing processes contribute to the steam explosion, i.e. the premixture formation before the explosion and the melt-water layer mixing during the explosion propagation itself. Suggestions for further analytical and experimental work are also given.

1. Introduction

A steam explosion may occur during a severe reactor accident when the molten core comes into contact with the coolant water (Berthoud, 2000). During the steam explosion the energy of the molten corium is transferred to the coolant water in a time scale smaller than the time scale for system pressure relief and so induces dynamic loading of surrounding structures. It represents an important nuclear safety issue because a strong enough steam explosion in a nuclear power plant could potentially jeopardize the containment integrity and thus lead to the radioactive material release into the environment (Theoufanous, 1995; Leskovar and Uršič, 2009).

One of the important conditions for the possible occurrence of an energetic steam explosion is the formation of an appropriate

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premixture of pre-fragmented melt and coolant. In nuclear reactor safety analyses steam explosions are primarily considered in the melt jet-coolant pool configuration where sufficiently deep coolant pool conditions provide complete jet breakup and efficient premixture formation. An extensive effort was put into the research of such steam explosions, recently also within the OECD SERENA program (Hong et al., 2013). On the contrary, much less attention was given to steam explosions in stratified melt-coolant configurations, i.e. a molten corium layer below a coolant layer. Stratified melt-coolant configurations were up to now believed as being unable to generate strong explosive interactions (Berthoud, 2000). Critical reviews of the assumptions and experimental data of several international programs and tests relevant to the steam explosion issue in the stratified melt-coolant configuration which lead to such a conclusion are presented in Grishchenko et al. (2013) and Kudinov et al. (2014). One of the important hypothesis questioned in Grishchenko et al. (2013) and Kudinov et al. (2014) is the assumption that there are no interfacial instabilities in a stratified configuration that can create an explosive premixture. The data which was used to support this hypothesis was obtained in experiments (e.g. performed by Frost et al., 1995) with mostly low temperature liquids, which showed rather low energy conversion efficiency and slow explosion propagation. In fact, the formation of a premixed layer was not even in the main focus of these experiments. Moreover, it was reported that special measures were needed in order to suppress the unwanted instabilities in the tests. From these experiments that were focused on studying the explosion propagation ability in undisturbed conditions useful information regarding the explosion propagation velocity could be obtained. The propagation velocity in relatively undisturbed hot/cold liquid interface conditions was in the range of 30–150 m/s (Frost et al., 1995; Bruckert, 1993). Within a fully developed premixture region in melt jet-coolant pool configuration experiments the propagation velocities may be much higher, extending in a wide range from 200 m/s to 1400 m/s (Huhtiniemi and Magallon, 2001; Leskovar et al., 2014). In the critical review given in Grishchenko et al. (2013) also non-explosive tests were included. However, those tests were not devoted to the investigation of the steam explosion phenomenon. For example, the most recent research programs MACE (ANL, USA), OECD/MCCI (performing small scale water ingression and crust strength tests—SSWICS, melt eruption tests—MET, and core-concrete interaction tests—CCI) and COTLES (NUPEC and NNC, Kazakhstan) were dedicated to the mechanisms of coolability under prototypic molten corium-concrete interaction conditions (Farmer et al., 2009). In the last period no research was dedicated to the issue of steam explosions in stratified configurations (Grishchenko et al., 2013).

However, the recently performed experiments in the PULiMS (Pouring and Underwater Liquid Melt Spreading) and SES (Steam Explosion in Stratified melt-coolant configuration) facilities (KTH, Sweden) with high melting temperature oxidic simulants of corium revealed that strong steam explosions may develop spontaneously also in stratified melt-coolant configurations (Grishchenko et al., 2013; Kudinov et al., 2014). In these experiments the steam explosions occurred during the ongoing underwater melt spreading. The key factors for the repeated occurrence of the explosions were the high melt superheat and the high water subcooling. Most importantly, the formation of a considerable melt-coolant premixed layer was observed in the tests prior to the explosions. Dynamic loads of about 60 t were measured and the assessed efficiencies were found to be quite high and reached up to 3.07%. The energy conversion ratio was comparable and even higher than in experiments carried out in the conventional melt jet-coolant pool configuration with prototypic materials applying a strong external trigger. The observed strong spontaneous steam explosions in stratified conditions have an important impact on the safety related issue of fuel coolant interactions in nuclear power plants:

- The observed spontaneous explosions in stratified configuration may provide a triggering mechanism for steam explosions in conventional melt jet-coolant pool configuration if the jet breakup is not complete.
- The amount of melt in stratified melt-coolant configuration available to participate in the explosion can be much larger than assessed before due to the formation of the premixed layer. In reactor conditions, where the melt can potentially spread on the large area of the cavity floor, the observed strong steam explosions may present an increased threat.

To assess the explosivity of the formed premixed stratified layer and to clarify which are the dominant mechanisms responsible for the melt-water mixing in stratified configuration, simulations of steam explosions in stratified conditions were performed with the MC3D computer code (Meignen et al., 2014a,b). The MC3D code, which is being developed by IRSN in France, is devoted to study steam explosions in the field of nuclear safety. Currently no method exists for the prediction of the premixed layer formation in stratified melt-coolant configuration. However, steam explosion simulations in stratified configuration may be performed with assumed premixed layer conditions, which provide important basic insight into the explosion development, especially regarding the premixed layer characteristics, the explosion propagation velocity and the explosion energetics.

The experiment PULiMS-E6 was the first exploratory test performed at KTH dedicated to steam explosions in stratified configuration with the emphasis on the investigation of the energetics of the explosion and the possible mechanisms for the development of the premixed layer (Grishchenko et al., 2013; Kudinov et al., 2014). The MC3D analysis of steam explosions in stratified configuration was therefore carried out in PULiMS like conditions. In the article the simulation results are analysed and discussed in comparison to available PULiMS-E6 experimental data.

2. Experiment simulation

In this section first the recent PULiMS (Pouring and Underwater Liquid Melt Spreading) experiments that were performed primarily to explore the underwater melt spreading, the terminal thickness of the spread melt and its coolability are presented (Konovalenko et al., 2012). Then the modelling approach and the MC3D code reference simulation results are presented in comparison to the PULiMS-E6 experimental results.

2.1. PULiMS experiments

Up to 78 kg of superheated molten oxidic simulant material (eutectic mixtures of Bi_2O_3/WO_3 and ZrO_2/WO_3) was poured in a shallow (20 cm) subcooled water pool so that the melt remains liquid when it reaches the bottom and can spread on the floor of the pool. The melt jet diameter was 20 mm.

A highly unstable melt-water interface with a quite developed premixed layer was observed in all experiments (Fig. 1). The premixed layer is formed by melt splashes, which can reach up to 80 mm above the melt surface (Grishchenko et al., 2013).

During the melt spreading instabilities at the melt-coolant interface are gradually growing, causing visible splashes and generation of waves on the coolant free surface in the test section (Fig. 2). One of the most probable mechanisms of the observed premixed layer formation is the growth, expansion and collapse of relatively large steam bubbles (Fig. 1). It is assumed that the collapse of bubbles in the subcooled water pool is a sufficiently frequent and energetic event to be the cause of the observed splashes and that the frequency of the process maintains the premixed layer (Grishchenko