VAPEX CODE ANALYSIS OF FARO L-33 TEST

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ABSTRACT

The analysis of the FARO L-33 test has been carried out with the VAPEX code. The FARO L-33 test has been implemented to study premixing and quenching processes for large mass (100 kg) of corium. The specific features of the test are: high subcooling (124 K), low pressure (4 bar), presence of noncondensable gas (argon) and triggered vapor explosion when melt reached the bottom of the vessel.

Special procedure, based on the Kelvin-Helmholtz approach and evaluation of steam film parameters, has been applied to estimate a size of melt droplets under melt jet fragmentation. Using of two different models of the jet fragmentation (which predicted both full fragmentation and non-full one) yielded practically the same results. No steam generation was revealed in the calculations. Level swelling, occurred in the test, is possibly due to hydrogen generation, which is not modeled in the code.

Modeling of vapor explosion, taken place in the test, yielded reasonable comparison with the test data in the case of using of significant void fraction in the jet region. It can be interpreted as occurrence of hydrogen in this region.

VAPEX analysis of the FARO L-33 test has shown reasonable agreement between experimental and calculated data, demonstrated capabilities of the VAPEX code to predict melt-coolant interaction phenomena taking place under severe accidents.

1 INTRODUCTION

In the course of severe accident evolution involving the melting of the core there might occur destruction of the reactor vessel along with the penetration of the melt into the cavity filled with water. Under this circumstances explosive interaction of melt and water mixture (vapor explosion) is possible.

Numerous experimental and theoretical investigation [1] of explosive interaction of melt and water mixture allow to distinguish four stages of large-scale vapor explosion:

1) premixing stage
2) triggering
3) formation and propagation of thermal detonation front
4) expansion of detonation products

Safety requirements of NPP in case of hypothetical vapor explosion demand the experimental and theoretical investigations of all vapor explosion stages. Experiments in large-scale test facility aiming the research of interaction of large mass of core region melt and coolant are of particular interest. Numerical modelling of large-scale experiments is one
of main phases of the computer models validation for predicting melt/water mixing and quenching.

L-33 test executed in the FARO test facility located in JRC (Ispra, Italy) was characterized with a mild energetic interaction triggered by an external explosive impulse. VAPEX code has been applied for post-test analysis of FARO Test L-33. The results of this analysis are presented in this article.

2 OVERVIEW OF DESCRIPTION OF VAPEX CODE

VAPEX code was developed at the Electrogorsk Research and Engineering Center. VAPEX consists of two independent programs VAPEX-P and VAPEX-D. Mathematical models of VAPEX-P and VAPEX-D are based on the methods of mechanics of multiphase fluids. VAPEX-P code (VAPor EXplosion – Premixing) is aimed for simulation of premixing stage. It considers three phases: liquid water, vapor and melt. For description of water's and vapor's dynamics it uses the Euler approach, and for description of melt dynamics it uses the Lagrangian approach. In order to describe the melt field, three phases are assumed: the jet, the melt droplets and debris bed at the bottom of the vessel. VAPEX-P code was successfully verified on results of experimental MAGICO and QUEOS [2,3]. VAPEX-D code (VAPor EXplosion –Detonation) is aimed for simulation of explosion stage during fuel-coolant interaction. Mathematical model of VAPEX-D code is based on microinteraction concept [4]. In accordance with this concept initially only a small quantity of coolant around each coarsely premixed melt mass "sees" the fragmenting debris coming off it. Special microinteraction phase, consisting of melt fragments and coolant adjoining to those fragments, was introduced in mathematical model of VAPEX-D code. So, there are four phases under consideration: namely, “microinteraction” fluid (m-fluid), coolant, fuel drops and fuel debris. Detailed description of mathematical model of VAPEX-D code is presented in [5].

3 EXPERIMENT FARO L-33

In the late 90's experimental series in the FARO test facility aiming the research of interaction corium and water were conducted. Initial conditions in this experimental series were chose for modelling of hypothetical severe accident in NPP, when melt of core region spills into the cavity filled with water. Low pressure (~2-5 Bar) and great subcooling of water (~100 K) should have promoted the triggering of vapor explosion, but spontaneous explosion didn't happen. Test L-33 was characterized with a mild energetic interaction triggered by an external explosive impulse.

A schematic of experimental facility FARO, which is located in JRC (Ispra, Italy), is presented in Figure 1. The FARO test facility consists of 5 main components; i.e., the furnace for melt generation, the intersection valve unit to isolate the furnace from the test section, the release vessel to hold up the melt temporarily for operational reasons, the FAT melt water interaction test vessel and the venting system to accommodate overpressures in excess of the design pressure (8 MPa). The FARO furnace consists of a pressure container (10 MPa), a fuel container, two electrodes and a release tube. The UO2-ZrO2 mixture is melted by direct heating of a granulate compacted between the electrodes. The intersection valve unit isolates the furnace from the test section during the interaction phase. It consists of two valves, which are closed sequentially after melt release. The release vessel is located inside the dome-shaped upper head of the FAT vessel. Its function is to hold the melt just for the time necessary to isolate the furnace from the test vessel and balance the release vessel and the FAT vessel pressures in order to ensure gravity release of the melt. The FAT test section consists of a pressure vessel of 1.5 m internal diameter and height about 2 m, designed for a pressure of 8 MPa and a temperature of 300 °C. Only this cylinder is filled with water, while the outer
annular space is part of the free board volume. A debris catcher is mounted in the lower part of the internal vessel. The volume occupied by the water (above the debris catcher bottom plate) is 0.628 m$^3$ and the corresponding free surface level is 1.62 m above the upper face of the debris catcher bottom plate. The test vessel is thermally insulated and disconnected from the steam/water separator and venting unit for this test.

![Figure 1: Schematic of the FARO test facility](image)

The initial conditions for Test L-33 are summarized in the Table 1. 100 kg of molten corium (80% UO$_2$-20% ZrO$_2$) under gravitation pour out from the release vessel in FAT inner vessel. Inner vessel contained 531 kg of subcooled water under pressure 0.41 MPa and temperature 294 K (subcooling 122 K).

A chronology of the events is summarised in the Table 2. Beginning of experiment was blasting of release valve membrane, after which the jet of melt began pouring out the release vessel. The melt jet touched surface of water in 0.4 s. In 1.01 s the leading edge of melt jet...
touched vessel bottom. In 1.124 s the trigger located on vessel bottom was activated. Trigger initiated the explosion. Pressure maximum was 10.5 MPa, the velocity of propagation of explosive wave was 370 m/s. Discharge of melt out of release vessel was finished by 2.4 s and in 2.84 s all melt had sunk into water.

**Table 1**: Experimental conditions for Test L-33

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt mass</td>
<td>100 kg</td>
</tr>
<tr>
<td>Melt composition</td>
<td>80 kg UO2 + 20 kg ZrO2</td>
</tr>
<tr>
<td>Melt temperature</td>
<td>3070 K</td>
</tr>
<tr>
<td>Free melt fall in gas</td>
<td>0.77 m</td>
</tr>
<tr>
<td>Water mass</td>
<td>531 kg</td>
</tr>
<tr>
<td>Water depth</td>
<td>1.62 m</td>
</tr>
<tr>
<td>Water temperature</td>
<td>294 K</td>
</tr>
<tr>
<td>Gas phase composition</td>
<td>99.65% Ar + 0.35% Steam</td>
</tr>
<tr>
<td>Gas phase volume</td>
<td>3.496 m³</td>
</tr>
<tr>
<td>Initial Pressure</td>
<td>0.41 Mpa</td>
</tr>
</tbody>
</table>

**Table 2**: A chronology of the events for Test L-33

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8.808</td>
<td>Start of melt release from furnace to release vessel</td>
</tr>
<tr>
<td>0.0</td>
<td>Start of melt delivery from the release vessel</td>
</tr>
<tr>
<td>0.400</td>
<td>Melt leading front contacts the water (pressure 0.5 MPa)</td>
</tr>
<tr>
<td>1.010</td>
<td>Melt leading front contacts the bottom plate</td>
</tr>
<tr>
<td>1.124</td>
<td>Trigger activated</td>
</tr>
<tr>
<td>1.130</td>
<td>Maximum pressure reached (10.5 MPa)</td>
</tr>
<tr>
<td>2.440*</td>
<td>Melt trailing edge passes the release vessel outlet (release vessel empty)</td>
</tr>
<tr>
<td>2.840*</td>
<td>All melt under water accounting for the level swell</td>
</tr>
</tbody>
</table>

* calculated

**4 ANALYSIS OF TEST L-33**

VAPEX-P code was used for simulation of premixing and quenching stages of FARO Test L-33. Special model, based on the Kelvin-Helmholtz approach and evaluation of steam film parameters, has been applied to estimate a size of melt droplets under melt jet fragmentation. It was found, that for FARO L-33 test condition, the characteristic size of droplets is around 3 mm. The jet fragmentation rate was estimated on the base of Saito correlation for jet breakup length.

Figure 2 demonstrated that the calculated water temperatures are in a good agreement with the experiments. It confirms the adequacy of models fragmentation and film boiling usable in VAPEX-P code. Both in experiment and in simulation the water temperature didn't reach saturation temperature. Figure 3 show that pressurization in the FAT vessel is initiated before the melt contacts with water and the rate of pressure increase is nearly constant during the period of melt release. Thus, one can conclude that pressurization is due to steam heat up. However, the calculated pressurization is lower than experimental one. This discrepancy can be explained by two peculiarities of the calculation. Firstly, we didn’t simulate the hydrogen generation, which leads to additional pressurization of about 0.015 MPa. Secondly, we didn’t simulate the melt fragmentation at the initial stage of the experiment (< 0.4 s), which was rather intensive according to the experimental images of the jet. Probably, at the initial stage of the experiment the fragmentation was not determined only by the melt leading edge.
instability, but also was determined by peculiarities of the melt release through release valve and orifice. The calculations reveal that the pressurization rate is very sensitive to the fragmentation in the gas space. However, we did not simulate the fragmentation in the gas space due to many uncertainties of this process phenomenology. Figure 4 show that the calculated gas temperatures are in a good agreement with the experimental ones from 0 s to 1.1 s (time of the vapor explosion). It should be noted, that the results of the VAPEX-P calculation were used as boundary conditions for initiating of the vapor explosion in VAPEX-D code, but the results of VAPEX-D calculations were not used as boundary conditions for calculations with VAPEX-P code during the stage after explosion.

![Figure 2: Temperature in the water region](image)

The value of the void fraction was adopted in accordance with experimental estimation of the averaged void fraction 5%. It should be noted that calculations of VAPEX-P code resulted in negligible amount of the gas phase in the water at the triggering moment. The VAPEX-D calculations of the explosion stage with void fraction about zero predicted unrealistically big pressure amplitude and very fast propagation of the thermal detonation. As mentioned above VAPEX-P code does not model hydrogen generation. This is the reason for underprediction of void fraction. So, we used the value of void fraction of 5%.

VAPEX-D code simulates explosive interaction of molten corium and water mixture triggering in 1.1 s. Initial distribution of melt droplets was adopted from premixing calculation by VAPEX-P code. Only liquid droplets with temperature greater or equal than 2830 K were considered in the explosion calculations, because the freezing droplets could not break up. The average volume of the melt was 0.024%, it is necessary to note that distribution
of droplet concentration along height was practically uniform diameter of the melt droplets – 3 mm, the temperature of the melt – 2900 K. The comparison of the calculated and test pressure histories on the vessel walls is presented in Figure 5-6. The amplitude and width of peaks coincide rather well. The average velocity of the propagation of thermal detonation is 360 m/s, which is similar to test value 370 m/s.

**Figure 4:** Temperature in the gas region

**Figure 5:** Pressure history at the level 0.715 m

**Figure 6:** Pressure history at the level 0.940 m
5 CONCLUSIONS

The analysis of FARO Test L-33 has been carried out with the VAPEX code. Numerical simulation of premixing and quenching provided rather good agreement with the test temperature of water and gas phase. Rather good agreement between the calculated results of the explosion interaction and the test data is an evidence of the proper prediction of the volume fraction of the melt droplets formed as a result of jet fragmentation. This value is crucial for determining the explosion intensity. The absence of the hydrogen generation model in the VAPEX-P code leads to under prediction of the pressure rise and void fraction. Modeling of vapor explosion, taken place in the test, yielded reasonable comparison with the test data.

VAPEX analysis of the FARO L-33 test has shown reasonable agreement between experimental and calculated data, demonstrated capabilities of the VAPEX code to predict melt-coolant interaction phenomena taking place under severe accidents.

REFERENCES


