Analysis of the experiment KROTOS-44 of melt-water explosive interaction using the code VAPEX

V I Melikhov\textsuperscript{1,2}, O I Melikhov\textsuperscript{1,2}, B Saleh\textsuperscript{1}, A A Shkel\textsuperscript{1} and M S Alkhutov\textsuperscript{1}

1 Moscow Power Engineering Institute “MPEI”, 14 Krasnokazarmennaya str., Moscow, 111250, Russian Federation
2 Electrogorsk Research and Development Center for Nuclear Power Plants Safety “ENIC JSC”, 6 Saint Constantine str., Electrogorsk, Moscow region, 142530, Russian Federation

E-mail: vladimir.melikhov@erec.ru

Abstract. The basic aim of KROTOS test facility is to provide experimental data on fuel coolant interaction phenomena during severe accidents in nuclear power plants. The presented article is devoted to validate the VAPEX code developed at the Department of NPP in Moscow Power Engineering Institute. The experiment K-44 was simulated using the VAPEX code, this experiment has a significant importance because it allows to clearly observe the growth and propagation of pressure waves. The calculated data for the explosion stage obtained by the VAPEX code are in a good agreement with the experimental data, which confirms the adequacy of the VAPEX code for the analysis of fuel coolant interaction in case of severe accidents in nuclear power plants.

1. Introduction
On the basis of a potentially severe accident of a water-cooled nuclear power plants, a variety of thermohydraulic, mechanical, physicochemical processes and phenomena are realized. At one of the late stages of severe accident development, it is possible that the melted core materials (corium) interacts with the remaining water in the reactor vessel, or when it flows from the vessel into the under-reactor cavity filled with water. The phenomenon of melt-water interaction is being actively studied in Russia and abroad [1].

One of the most famous experimental programs for studying corium - water interaction was carried out at the KROTOS facility in the Joint Research Center (Ispra, Italy) [2]. The main goal of these experiments was to obtain data for the explosive interaction of high temperature melt with water. In addition, the KROTOS experimental data verify the adequacy and the quality of the modeling computer codes designed to calculate the explosive interaction of corium with water. In this work, using the code VAPEX [3–6], we performed a computational analysis of the KROTOS-44 experiment.

2. Description of KROTOS test facility
The experimental setup is shown in figure 1, it consists of three main parts; radiation furnace located above, pipe connecting the furnace to the pressure vessel and the test section located below. First, the material is heated in the radiation furnace, then it enters the connecting pipe (length 5m) which lead the melt into the test section filled with water. The main measured parameters in the KROTOS...
experiments were: pressure, temperature and water level. Despite the fact that $\text{Al}_2\text{O}_3$ (which was used as melt in a number of experiments at the KROTOS facility) is not a prototype of the melt materials in nuclear reactors. The experiments which use $\text{Al}_2\text{O}_3$ are extremely important for the validation of codes which simulate steam explosions, due to the inherent wave dynamics of such experiments and the associated models of fragmentation and fast heat transfer. Among these experiments the K-44 experiment should be distinguished. In the experiment K-44, the initial conditions are well defined and detailed measurements are made, which make it possible to clearly observe the growth and propagation of pressure waves. The propagation velocity of the pressure wave was in the range from 450 m/s to 1000 m/s, which was accompanied by an increase in pressure to ~ 50 MPa.

![KROTOS test facility](image)

**Figure 1.** KROTOS test facility.

3. **Parameters and main results of the experiment KROTOS-44**

The initial conditions for simulating explosive interaction were obtained on the basis of the analysis of the experimental data of KROTOS K-44 [2] and are presented in Table 1 with the corresponding comments.

| Zone                  | Quantity | Value    | Comments                                                                 |
|-----------------------|----------|----------|--------------------------------------------------------------------------|
| Preliminary mixing    | Height   | 750 mm   | 1. At the initiation of the steam explosion, the melt front was at the elevation K1 (150 mm)  |
|                       |          |          | 2. “The tail” of the melt was between elevations K4 and K5 (approximately 850 mm) |
|                       | Diameter | 200 mm   | Full diameter of the test section                                       |
|                       | Melt fraction | 0.032-0.02 | It varied linearly from the value 0.032 at elevation                  |
150 mm to 0.02 at elevation 850 mm. An average value of 0.026 was taken, which is 3% of the total melt.

| Property                  | Value               |
|---------------------------|---------------------|
| Steam content             | 0.09                |
| Water fraction            | 0.878-0.890         |
| Melt temperature          | 2673 K              |
| Gas temperature           | 1000 K              |
| Water temperature         | 363 K               |
| Average particle size     | 15 mm               |
| Steam content             | 0.165               |
| Water fraction            | 0.845               |
| Water temperature         | 363 K               |
| Average particle size     | 15 mm               |
| Trigger Location          | In the center of the bottom plate |
| Maximum pressure          | 14.8 MPa            |

Below the preliminary premix zone:

- Height: 150 mm
- Melt fraction: 0
- Diameter: 200 mm
- Steam content: 0
- Proportion of water: 1
- Water temperature: 363 K

Above the preliminary premix zone:

- Height: 379 mm
- Melt fraction: 0
- Steam content: 0.165
- Water fraction: 0.845
- Water temperature: 363 K

4. VAPEX Code

The VAPEX code (VAPor EXplosion) has been developed for a long time at the Department of NPP of National Research University "Moscow Power Engineering Institute". Earlier, the problems of mixing the melt with water, which is accompanied by a relatively slow (time scale of ~ 1 s) increase in pressure caused by the evaporation of water, were mainly studied using this code. In this work, the VAPEX code is used to analyze the explosive interaction of corium with water (time scale ~ 1 ms). The mathematical model of the studied processes is described in detail in [3-6]. In this article we introduce only its main features.
Consider a steam-water mixture in a region containing drops of a high-temperature melt. Under certain hydrodynamic conditions, the melt droplets can be split into many small fragments, which leads to a sharp increase in the interfacial surface and consequently to an increase in the heat flux from the melt to the steam-water mixture. This process is described using the mechanics of multiphase flow [7]. The following phases are considered: large (initial) drops of the melt (f-phase); small fragments of melt droplets formed during fragmentation (db-phase); non-condensing gas (a-phase); a cooler (water) that is not in direct contact with the melt (“remote” cooler, l-phase); steam (v-phase, is involved in the process of micro interactions). The system of equations determining the propagation of a thermal detonation wave considers the exchange of energy, momentum, and mass between phases. This system includes three equations of conservation of energy, three equations of conservation of momentum, and four equations of continuity.

5. Comparison of calculated and experimental data

Figure 2 shows the nodalization scheme of the KROTOS-44 experiment. The initial data for the calculation were taken from table 1. The calculation area is a cylinder of 1.59 m height and 0.2 m diameter. The zone was divided by height into 318 cells of the same length (Δz = 5 mm), one cell was modeled along the radius. The height of one cell is 5 mm. The trigger was modeled in the lower cell, the pressure in the trigger cell was 14.8 MPa. At the moment of starting the trigger (the phase of steam explosion initiation), the phases velocities were taken equal to zero, since these velocities are much lower than (by two orders of magnitude) the velocities developed during the steam explosion.

![Figure 2. Scheme of the KROTOS-44 experiment.](image)

Figure 3 shows a comparison of the experimental results of KROTOS K-44 setup with calculation results obtained by VAPEX-D code. There is a good agreement between the amplitude of the pressure peaks, as well as their width.
6. Conclusion
The KROTOS experiment of melt-water explosive interaction was simulated using the code VAPEX. Based on the analysis of experimental data, the initial conditions preceding the explosion are determined, namely, the length of melt-water mixing zone, the parameters in this zone are: volume fraction of melt, volumetric steam content and the size of melt particles. These parameters were set as initial conditions into the code VAPEX. A good agreement was obtained between the calculated and experimental data for the explosion stage. This indicates the validity of the basic principles of the mathematical model, and provides the basis for the subsequent usage of the code VAPEX for the analysis of corium-water interaction in case of severe accidents in nuclear power plants.

Acknowledgments
This study was funded by RFBR, projects № 18-08-01048 and № 20-08-00584.

References
[1] Meignen R, Raverdy B, Picchi S and Lamone J 2014 The challenge of modeling fuel–coolant interaction: Part II – Steam explosion Nucl. Eng. Des. 280 528–41.
[2] Huhtiniemi I, Magallon D and Hohmann H 2001 Results of recent KROTOS FCI tests: alumina versus corium melts Nucl. Eng. Des. 204 391–400
[3] Melikhov V I, Melikhov O I and Sokolin A V 2002 Melt-water explosive interaction: VAPEX-D code simulation High Temp. 40 428–436
[4] Melikhov V I, Melikhov O I and Yakush S E 2007 VAPEX code-aided analysis of large-scale experiments in corium-water interaction High Temp. 45 509–517
[5] Melikhov V, Melikhov O, Yakush S and Rtishchev N 2011 Validation of fuel-coolant interaction model for severe accident simulations Sci. Technol. Nucl. Install. 2011 Article ID 560157
[6] Gudemenko D V, Melikhov V I and Melikhov O I 2017 Styding the thermal detonation process using the microinteraction model MPEI Vestnik 2 32-29 (in Russian)
[7] Nigmatulin R I 1990 Dynamics of Multiphase Media (New York: Hemisphere)