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EVALUATION OF STEAM EXPLOSION (ESE) : PREMIXING

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ABSTRACT

The steam explosion phenomenon is generally divided into four stages: premixing of melt and coolant, triggering of explosion, explosion escalation and propagation, expansion and work production. This contribution is assessing the first stage of steam explosion process while taking advantage of alternative approach, namely probabilistic multiphase flow equations.

First, the equations and method of their solution are briefly discussed. Following the experiments "Billet 1000" (Oulmann and Hamon, 1994) the geometry was modelled using finite difference technique. The results for four phase mixture (melt, water, vapor, air) are presented in form of graphs depicting velocity, pressure, and phase presence probability fields. At the end, the conclusions and future plans are given aiming at better steam explosion understanding.

NOMENCLATURE

D	diameter of fragments
E	energy
g	gravity
h	enthalpy
J	vapor generation
$\vec{M}$	sum of various forces
p	pressure
q	heat source density
r	radial coordinate
t	time
T	temperature
$\vec{u}$	velocity
z	vertical coordinate

Greek

α	phase presence probability
Γ	dimensionless vapour generation
ν	kinematic viscosity
ξ	thermal conductivity
ρ	density
σ	surface tension

Subscripts

k	phase index
0	characteristic dimension
r	radial vector components
z	vertical vector component

INTRODUCTION

In case of prolonged and complete failure of nuclear reactor normal and emergency coolant system, the fission material decay heat would cause melting of reactor core. The melt may come into contact with either subcooled or saturated coolant. An explosion due to the violent interaction between two fluids may be triggered. Under favourable conditions the local interaction evolves into shock propagating through the mixture, fragmenting molten fuel and becoming a self sustained reaction (Horvat and Marn, 1995).

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In general, four stages of steam explosion phenomenon have been identified and experimentally studied:

1. mixing of hot liquid (molten fuel) and more volatile liquid (coolant);
2. triggering as a result of local instabilities of the vapor film between molten fuel and coolant;
3. explosion escalation and propagation;
4. vapor expansion doing work on surrounding .

If a sufficiently large mass of melt mixes with the coolant and a steam explosions results, the subsequent expansion of vapor might cause RPV and safety containment failure. This contribution studies the first stage of a steam explosion: premixing, which controls the strength of melt-coolant interaction.

To simulate it following the experiments of Oulmann and Hamon (1994) one had to develop the system of equations (continuity, momentum, energy) with the following boundary conditions and solve them. In the calculations the cylindrical jet of 0.10m diameter consisting of molten ZrO_2 with initial temperature of 1273K was used to penetrate into cylindrical vessel of 1.5m diameter and 1m high containing liquid water at 293K. Initial valocity of jet was 2.2m/s. The water was initially 0.67m high with the rest of the vessel filled with air. The initial pressure was 1 bar, and temperature of the air was that of the liquid water.

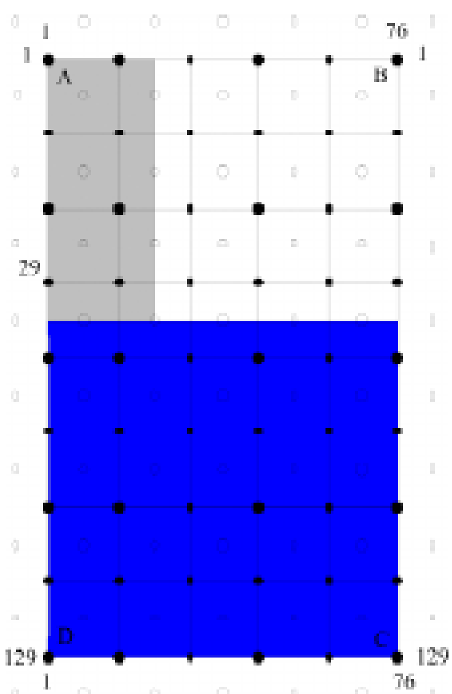

Figure 1: Initial conditions

The geometrical setup of the containment with symmetry axis on the left is shown in Fig. 1. In the center there is a molten ZrO_2, on the bottom is water, and on the top is air. Because of axisymmetry of the phenomenon the size of the numerical mesh have to cover only one half of the containment cross section. The basic grid size is 129 (length) x 76 (radius) mesh points.

CONSTITUITIVE EQUATIONS AND METHODS OF SOLUTION

The idea was to describe multiphase flow with statistical averaging (Molodtsof and Muzyka, 1989), define α_k as probability of presence to find phase k at time at the point $\vec{r}$:

$$\alpha_k(\vec{r},t) = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} X_{k,i}(x,t)\,, \tag{1}$$

where X_k is characteristic function of phase k. Using statistical ensemble averaging over the set of identical experiments the following equations where developed (Leskovar and Marn, 1994):

continuity equation

$$\frac{\partial \alpha_k}{\partial t} + \frac{\alpha_k}{\rho_k}\left(\frac{\partial \rho_k}{\partial t} + \frac{D_k^3 g}{\nu_k^2}\left(\frac{\rho_k u_r}{r} + \frac{\partial(\rho_k u_r)}{\partial r} + \frac{\partial(\rho_k u_z)}{\partial z}\right)\right) + \\ + \frac{D_k^3 g}{\nu_k^2}\left(u_r \frac{\partial \alpha_k}{\partial r} + u_z \frac{\partial \alpha_k}{\partial z}\right) = \frac{\Gamma_k}{\rho_k} \tag{2}$$

momentum equation

$$\frac{\partial u_r}{\partial t} + \frac{D_k^3 g}{\nu_k^2}\left(u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z}\right) = \\ = \frac{1}{\rho_k}\left(-\frac{\sigma_k}{D_k^2 \rho_k g}\frac{\partial p}{\partial r} + M_{k,r} + \frac{\Delta u_r \Gamma_k}{\alpha_k}\right), \tag{3}$$

$$\frac{\partial u_z}{\partial t} + \frac{D_k^3 g}{\nu_k^2}\left(u_r \frac{\partial u_z}{\partial r} + u_z \frac{\partial u_z}{\partial z}\right) = \\ \frac{1}{\rho_k}\left(-\frac{\sigma_k}{D_k^2 \rho_k g}\frac{\partial p}{\partial z} + \rho_k g_z + M_{k,z} + \frac{\Delta u_z \Gamma_k}{\alpha_k}\right). \tag{4}$$

and energy equation

$$\frac{\partial h_k}{\partial t} + \frac{D_k^3 g}{\nu_k^2}\left(u_r \frac{\partial h_k}{\partial r} + u_z \frac{\partial h_k}{\partial z}\right) = \\ = \frac{1}{\rho_k}\left(\frac{\xi_k T_k}{\rho_k h_k \nu_k}(q_k + E_k) + \frac{\Delta h_k \Gamma_k}{\alpha_k}\right). \tag{5}$$

Vector $\vec{M}_k$ includes all forces acting on particular phase k except pressure force and gravity. As a result of statistical averaging of multiphase flow many fluctuation quantities appear which cannot be defined deterministically. They are proposed probabilistically meaning that appropriate probability density function is chosen and applied accordingly. In this model all these quantities are also include in vector $\vec{M}_k$.

E_k in energy equation is treated similarly. Equations are presented in their dimensionless form, therefor the several dimensionless parameters have to be introduced :

$$
\begin{aligned}
& u_k = \frac{D_k^2\, g_0}{\nu_k},\ t_0 = \frac{D_k^2}{\nu_k},\ p_0 = \frac{\sigma_k}{D_k},\ J_{k,0} = \frac{\rho_k}{t_k}, \\
& M_k = \rho_k\, g_0,\ E_{k,0} = \frac{\xi_k T_k}{D_k^2}, \\
& \frac{\vec{u}_k}{u_k} = (u_r, u_z)_k,\ \frac{\vec{r}_k}{D_k} = (r, z)_k,\ \frac{t}{t_0} \to t,\ \frac{p}{p_0} \to p, \\
& \frac{\vec{g}}{g_0} = (0, g_z),\ \frac{h_k}{h_{k,0}} \to h_k,\ \frac{J_k}{J_{k,0}} \to \Gamma_k, \\
& \frac{\vec{M}_k}{M_k} = (M_{k,r}, M_{k,z}),\ \frac{E_k}{E_{k,0}} \to E_k, \\
& DL1 = \frac{D_k^3\, g_0}{\nu_k^2},\ DL2 = \frac{\sigma_k}{D_k^2 \rho_k\, g_0},\ DL3 = \frac{\xi_k T_k}{\rho_k h_k \nu_k}.
\end{aligned}
\tag{6}
$$

Pressure equation is derived from momentum equation (3, 4) taking into account continuity equation (2) to read as

$$
\begin{aligned}
& DL2 \cdot \left(\sum_3 \frac{\alpha_k}{\rho_k} \right) \left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} + \frac{\partial^2 p}{\partial z^2} \right) + \\
& + DL2 \cdot \left(\sum_3 \frac{1}{\rho_k}\frac{\partial \alpha_k}{\partial r} \right) \frac{\partial p}{\partial r} + DL2 \cdot \left(\sum_3 \frac{1}{\rho_k}\frac{\partial \alpha_k}{\partial z} \right) \frac{\partial p}{\partial z} = \\
& = -\sum_3 DL1 \cdot \left(\frac{\partial(\alpha_k u_r)}{\partial r} + \frac{\alpha_k u_r}{r} + \frac{\partial(\alpha_k u_z)}{\partial z} \right) \left(\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_z}{\partial z} \right) + \\
& - \sum_3 DL1 \cdot u_r \left(\frac{1}{r}\frac{\partial(\alpha_k u_r)}{\partial r} + \frac{\partial^2(\alpha_k u_r)}{\partial r^2} - \frac{\alpha_k u_r}{r^2} + \frac{\partial^2(\alpha_k u_z)}{\partial r \partial z} \right) - \\
& - \sum_3 DL1 \cdot u_z \left(\frac{\partial^2(\alpha_k u_r)}{\partial r \partial z} + \frac{1}{r}\frac{\partial(\alpha_k u_r)}{\partial z} + \frac{\partial^2(\alpha_k u_z)}{\partial z^2} \right) \\
& - \sum_3 DL1 \cdot \alpha_k \left(\left(\frac{\partial u_r}{\partial r} \right)^2 + \left(\frac{\partial u_z}{\partial z} \right)^2 \right) + \\
& + \sum_3 DL1 \cdot \alpha_k \left(u_r \frac{\partial^2 u_r}{\partial r^2} + u_z \frac{\partial^2 u_z}{\partial z^2} + 2\frac{\partial u_z}{\partial r}\frac{\partial u_r}{\partial z} + u_z \frac{\partial^2 u_r}{\partial r \partial z} \right) \\
& - \sum_3 DL1 \cdot \alpha_k \left(u_z \frac{\partial^2 u_r}{\partial r \partial z} + \frac{u_r}{r}\frac{\partial u_r}{\partial r} + \frac{u_z}{r}\frac{\partial u_r}{\partial z} \right) + \\
& - \sum_3 DL1 \cdot \left(\frac{\partial \alpha_k}{\partial r}\left(u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z} \right) + \frac{\partial \alpha_k}{\partial z}\left(u_r \frac{\partial u_z}{\partial r} + u_z \frac{\partial u_z}{\partial z} \right) \right) \\
& + \sum_3 \frac{\alpha_k}{\rho_k}\left(\frac{\partial M_{k,t}}{\partial r} + \frac{M_{k,r}}{r} + \frac{\partial M_{k,z}}{\partial z} \right) + \left(\frac{M_{k,r}}{\rho_k}\frac{\partial \alpha_k}{\partial r} + \frac{M_{k,z}}{\rho_k}\frac{\partial \alpha_k}{\partial z} \right)
\end{aligned}
\tag{7}
$$

The continuity, momentum, and energy equations were solved using Lax-Wendroff scheme thus ensuring second order temporal and spatial accuracy. The pressure equation was solved using Alternating Direction Implicit scheme which was chosen for its robustness and ease of application. To improve the numerical accuracy of model, the discretized form of equation (7) was developed using already discretized version of the equations (3,4) and applying discretized version of equation (2).

During numerical simulation the Courant-Friedrichs-Lewy stability criterion was incessantly checked. The Courant number reached value of 0.9 for the highest velocity component and the typical time step was 0.002s. The moving front was usually spanned anywhere between 1 and 5 grid points.

These equations were solved in axisymmetric two dimensional domain using initial conditions from fig. 1. The main assumption used in this contribution is so called coupled velocity field (Marn and Leskovar, 1995b). It means that velocities of all phases remain equal in same mesh point. The pressure was described with single pressure field, too.

With appropriate scaling of vector $\vec{M}_k$ and E_k the velocity and pressure field were stabilized and criteria for equality of phase velocities were implemented.

RESULTS

The following figures (2 through 10) present velocity field, melt and steam phase probability field and temperature field of the mixture. Due to poor clarity, water and air phase probability fields are not presented.

Figures 2, 3 and 4 show the temporal evolution of the velocity field. Arrows and shadowing show the moving direction of fluid and the amplitude of the velocity field. Darker cells represent higher velocities. In order to enhance clarity 2.4 mesh cells are lumped into single point.

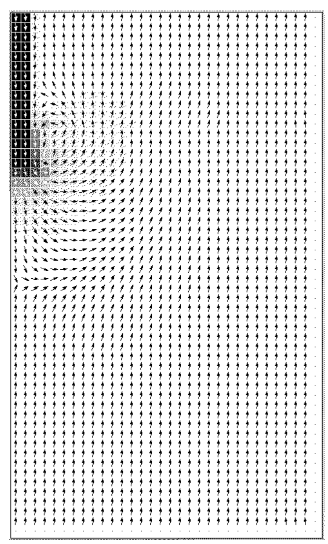

Figure 2: t = 0.0s

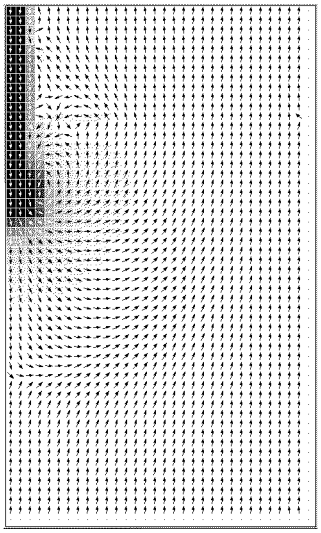

Figure 3: t = 0.1s

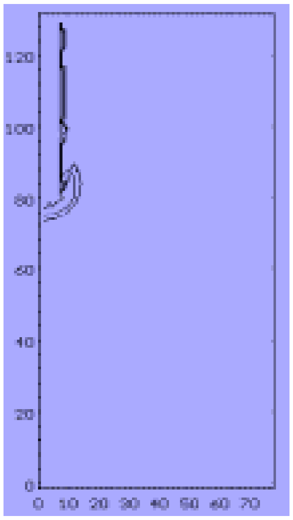

Figure 5: t = 0.1s

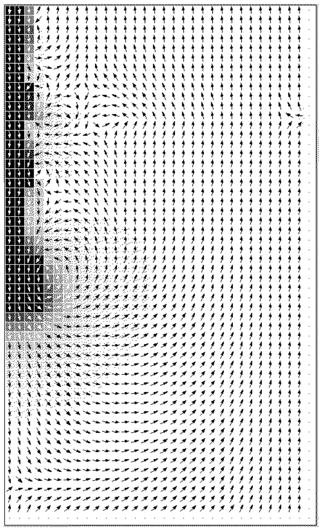

Figure 4: t = 0.2s

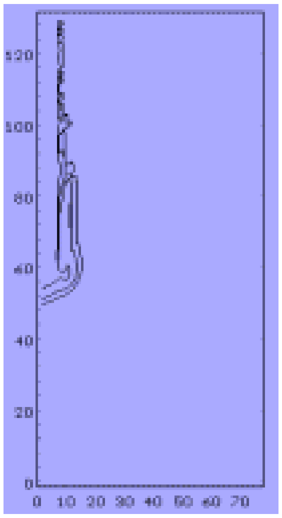

Figure 6: t = 0.2s

During the penetration the velocity of melt jet is decreased, but velocity of neighbouring coolant is increased instantaneously. The large vortex is made depicting so called inverted mushroom structure.

Figures 5 and 6 show the temporal evolution of melt phase probability field. The figures are taken after 0.1s and 0.2s after beginning of the transient. Isolines displaying values of phase probability: 0.5, 0.005 and 0.00005. One can observe the decomposition of jet head while it penetrates into bulk of liquid water.

Figures 7 and 8 show the temporal evolution of steam phase probability field. The isolines values of phase probability and the time steps are the same as in previous figures.

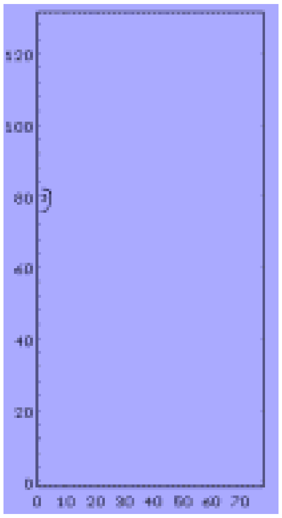

Figure 7: t = 0.1s

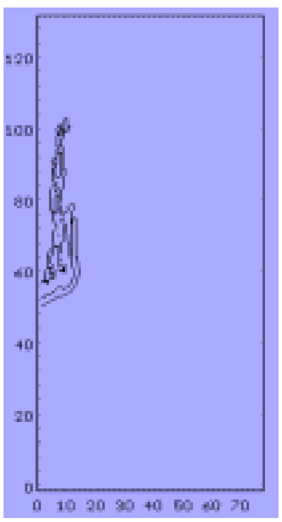

Figure 8: t = 0.2s

At time 0.0s the steam is not present as water did not reach the saturation temperature. Because of low initial water temperature only modest steam cloud is generated when melt jet moves down for 20 mesh points (0.1s). After reaching the saturation temperature the generation of steam is rapidly increased because of increasing surface contact between melt and water.

Figures 9 and 10 show unified temperature field outlined by isotherms. The unified field was defined as field of temperatures of phases present in particular mesh point with highest phase presence probability. It is constructed for clarity of presentation only. The contours show the values of 293K, 763K, and 1273K, respectively.

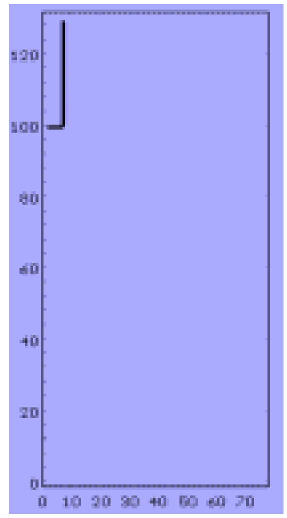

Figure 9: t = 0.1s

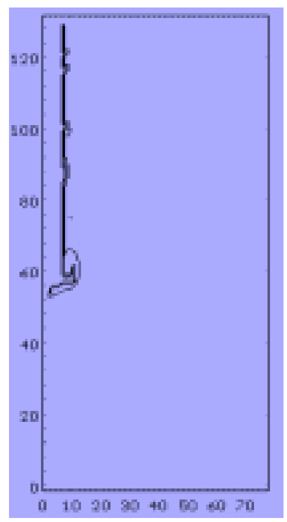

Figure 10: t = 0.2s

With time increasing the isotherms stretch down toward bottom of the vessel. Because of vaporization the temperature field stays poorly developed due to rapid melt fragments quenching.

CONCLUSIONS

Our group walked a long way from early attempts to numerically describe a multiphase mixture as fundamental understanding of first phase of steam explosion (Leskovar and Marn, 1995a). At present stage a general 2D model for treatment of multiphase transport was developed and demonstrated to the specific case of four phase mixture movement. This work is specifically reporting preliminary calculations to demonstrate capability.

The velocity, phase probability and temperature field were calculated during the melt jet breakup and premixing stage of steam explosion. The main limiting assumption in the present work is the single velocity field (so called coupled field) which means that velocities of all phases are equal at the same mesh point. Second limiting assumption is incompressibility of individual phases. This enables to simulate pressure waves in four phase mixture which accompany first stage of steam explosion (Horvat, 1995). These assumptions are used to arrive at solution of the equations but are currently under review and will be abandoned in the next version of the code.

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