Transactions of the Korean Nuclear Society Spring Meeting
Gwangju, Korea, May 30-31, 2013

Analysis of core expansion and energy behavior during severe accident of sodium cooled fast reactor

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1. Introduction

Research on severe accident in fast reactor such as a CDA has been attracting more attention since the Fukushima Dai-ichi nuclear power plant accident in 2011. The main reason for such attention is the fact that the rearranged core materials can produce a large increase in reactivity and recriticality, which is unique to fast reactors. If such a rearrangement of core materials should occur rapidly, there would be a high rate of reactivity increase producing power excursions. The released energy from such an energetic recriticality might challenge the reactor vessel integrity.

2. Analysis of core explosion during CDA

The evaluation of CDA energy release is conducted using the CDA-ER code developed in this work, based on the Bethe-Tait method modified by Nicholson [1]. Calculations were performed for the super prompt power excursions of the KALIMER-150 core shown in Fig. 1, initiated by the reactivity insertion. The whole core meltdown is assumed in the calculation.

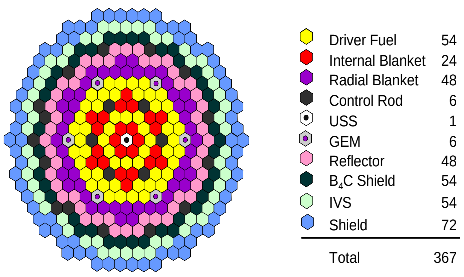

Fig. 1 KALIMER-150 core configuration

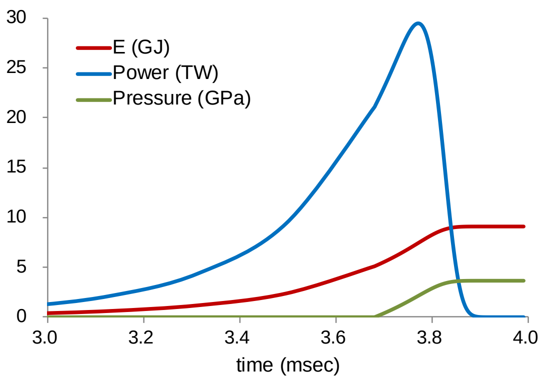

Fig. 2 Calculation results without Doppler effect when α = 100 $/s

Figure 2 shows the calculated results of energy, power and pressure when reactivity insertion rates were assumed to be 100$/s, which is usually understood to be the upper limit of the CDA analysis. The estimated maximum energy release, power, and pressure were 9.1GJ, 29.5TW and 3.7GPa, respectively, and these are used as the initial core condition for its explosion calculation.

The analysis to estimate the core behavior during an explosion from the CDA in a sodium cooled fast reactor (SFR) is carried out. The theory and analysis approach of an underwater explosion are applied to the present core explosion evaluation, considering the fact that the plant, i.e., SFR, uses liquid metal sodium as a coolant surrounding the core. Hydrodynamic and thermodynamic computations are performed using the code developed in this work for the simulated core disruptive accidental condition. The transient pressure, temperature, and expansion of the core bubble are calculated through solving the equation of the state of ideal gas and the nonlinear governing equation of the momentum conservation in one-dimensional spherical coordinates. The core is treated as an adiabatic homogeneous ideal gas but the inertial effects of the gas are ignored in the calculation. The motion of a spherical explosion bubble oscillating in an incompressible homogeneous inviscid fluid are numerically computed using an ideal gas model for the behavior of the bubble interior [2].

It is assumed that a sharp interface exists between the core and surrounding fluid during the expansion process. Heat and mass transfers across the interface are neglected due to a very short time scale of interaction, which is on the order of milliseconds. In addition, a shock wave emission from an explosion into a surrounding medium is not evaluated. Instead of assuming a shock wave propagation, the heat and mass transfers, a subsequent isentropic expansion is assumed [3].

Though this work is thought to be too conservative from a practical point of view, it is aimed at observing the consequence limit of most destructive accident conditions in a fast reactor through a scoping approach.

3. Formulations

Figure 3 shows the simulated domain comprised of core bubbles of the initial and fully expanded states, cover gas, i.e., He, and sodium in the rectangular shaped reactor vessel. The height and width of the reactor vessel are 18 m and 7.4 m, respectively. The cover gas is above the sodium pool to absorb the pressure transients in the reactor system, set to about one atmospheric pressure during normal plant operation.

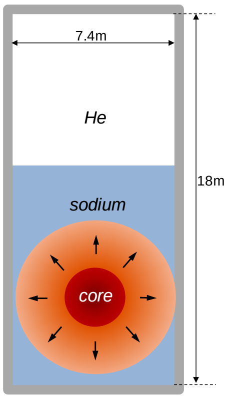

Fig. 3 Core bubble in reactor vessel

Since the bubble expansion process is regarded as reversible adiabatic, the following identity holds over the procedure:

$$de = Tds - Pdv = -Pdv \qquad (1)$$

where s is the entropy, P is the pressure, and v is the specific volume.

Since γ is constant over this process, the pressure and specific volume maintain the following relation,

$$Pv^{\gamma} = const. \qquad (2)$$

It is assumed that the bubble maintains a spherical shape and the surrounding liquid thus has only a radial velocity. To derive the governing equations for the motion of the surrounding fluid rushing away from bubble surface, a Euler momentum conservation equation for an incompressible fluid in spherically symmetric motion is used [4], which is

$$\frac{\partial u}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial t}(r^2 u^2) = -\frac{1}{\rho_w}\frac{\partial P}{\partial r} \qquad (3)$$

where u is the radial velocity, r is the distance from the origin, and ρ_w is the surrounding fluid density

4. Results

The numerical computations are conducted for a core explosion surrounded with sodium in the reactor vessel described in Fig. 3 using the following initial conditions. The explosive is supposed to be the fuel materials. Therefore, the total explosive (9,976 kg) is assumed to turn almost instantaneously into a gas volume of 1.38 m^3. Taking the initial gas volume as a sphere, the core bubble radius is assumed to become 0.69m. The hydrostatic pressure P_∞ and sodium density are taken to be 180kPa and 828kg/m^3, respectively.

Fig. 4 shows the calculated bubble radius with time. The bubble touches the wall of the reactor vessel, whose inner radius is 3.7 m at 14.6ms.

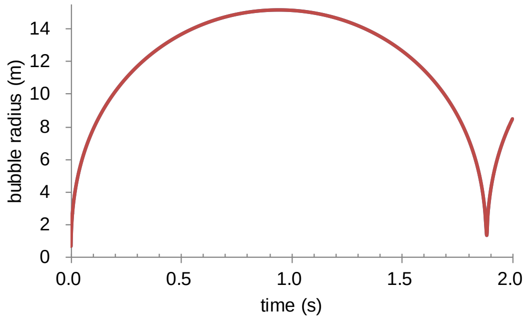

Fig. 4 Bubble radius with time (different scale from below)

Fig. 5 shows the calculated results of the energy distributions during 0.015s after the explosion. The total energy is calculated to be 2.52GJ, and remains constant throughout the calculation. The energy balance is almost exactly met among the sodium kinetic energy, expansion work and internal energy of the bubble. At 0.01 s, for example, the kinetic energy of the sodium is 2.50 GJ, while the expansion work and internal energy of the bubble are 0.023 GJ and 0.284 MJ, respectively.

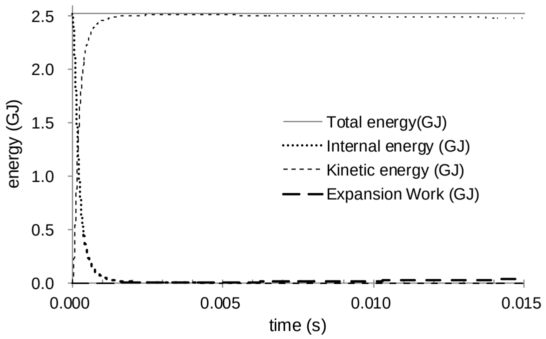

Fig. 5 Distributions of the total energy and its components over time

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