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Development of Equation of State for a SFR Metal Alloy Fuel

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1. Introduction

The density-dependent equations for state of pressure-energy density relationship were developed in this study for U-Pu -Zr alloy for analyzing the core disruptive accident(CDA) of the metal-fueled SFR core. The equations of state for the single-phase liquid of the metallic alloy fuel were derived based on the van der Waals model.

In this study, a core disassembly analysis in the sodium-voided core of the KALIMER-150 [1]was performed using the VENUS-II code [2] for the reactivity insertion rates of 100 $/s, which has been widely considered to be the upper limit of the ramp rates due to a fuel compaction. This extreme case of the reactivity insertion rate also serves to test the applicability of the density-dependent equation of state of pressure-energy relationship utilized in this study for the single phase liquid region far above the melting temperature of the uranium.

2. Equation of State

The principal relation necessary for the CDA analysis is the pressure as a function of energy and volume for hydrodynamic calculations. The initial configuration of sodium-voided core is such that liquid fuel above the melting point is interspersed with void spaces left in the core when the coolant is expelled. As the temperature rises, the voids are filled with the expanded liquid thus producing saturated vapor pressure. If the liquid reaches the threshold energy to fill the voids completely, the pressure begins to rise rapidly.

Based on the first law of the thermodynamic principle, pressure, p, can be written as a density-dependent threshold type of equation of state, if the specific heat, c_v, is independent of the temperature T and the specific volume, v :

$$p = \kappa\rho(E - E^*) \qquad (1)$$

where ρ is the density of the material, E the internal energy, E^* the threshold energy and κ is the constant to be determined.
By a simple comparison of the van der Waals equation and a thermodynamic expression for the pressure, the functions for κ, E and E^* can be written in terms of the constants *a* and *b*:

$$\kappa = \frac{R_0 / c_v}{1 - b\rho} \qquad (2)$$

$$E = c_v T - a\rho + E_0 \qquad (3)$$

and

$$E^* = E_0 + a\rho[\frac{c_v}{R_0}(1 - b\rho) - 1] \qquad (4)$$

where E_0 is a constant which determines the reference point for the measurement of the internal energy[3,4].

The following input data is assumed for the calculations of the numerical values of the constants a and b, and thereby to evaluate $\kappa, E*$ and E_0 for U-Pu-Zr alloy[5] ;

$p_c = 218.4MPa^3$,
$T_c = 8{,}800K$,
$v_c = 0.324\ cm^3/gm$,
and
$\rho_m = 13.8gm/cm^3$, $\rho_s = 15.0gm/cm^3$

It follows then that the constants a, b and E_0 of the Vander Waals model have the values :
$a = 123.1J.cm^3/gm^2$,
$b = 0.0667cm^3/g^2$
and
$E_0 = 1{,}515$ J/g

Figures 1 and 2 show the change of κ and E^*, respectively, as a function of fuel density. As the density increases, so does κ. It reaches its maximum value with the fuel density of 14 g/cm^3 .The threshold energy E^* shows its maximum at the density of 2 g/cm^3.

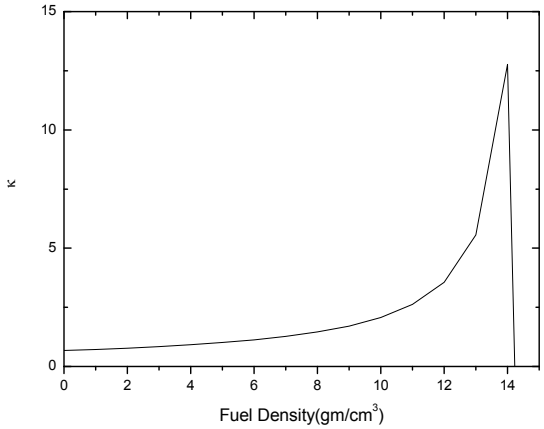

Fig. 1 Change of κ as a function of fuel density

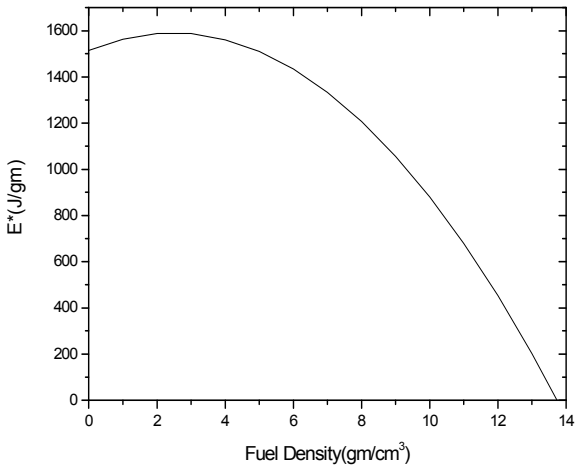

Fig. 2 Change of Threshold Energy E* as a function of fuel density

3. Analysis Results

At the start of the core disassembly analysis, the core is assumed to be at prompt critical. The core thermal power at prompt critical is assumed to be 3,920 MW, which is ten times the steady state power. The mean temperatures of the driver fuel regions are assumed to be above the melting temperature of the fuel (1,550K). It was assumed in this study that the fuel pressure remains essentially zero until the internal energy of the fuel reaches the threshold energy for the single phase liquid region.

Calculations showed that core power reaches its maximum at 3,144Gw at 3.48 ms, which is about 800 times the initial power. The total energy released during the excursion amounts to 6,980 MJ. Pressure rises first at the mesh cell number (4,10) located at the axial mid-plane of the inner driver fuel assemblies , where the peak power occurs representing the most reactive fuel assemblies in the core. The pressure at the cell jumpstarts to 156 atm at about 5.39 ms, when the fuel becomes a single phase liquid. The local pressure rapidly increases first and drops down as the fuel density decreases. The power excursion is terminated at 5.65 ms as the negative reactivity feedback brings the core reactivity far below critical state. The temperature at the cell increases from 7,770 K to 14,000 K at 5.39 ms.

4. Conclusion

Calculations have been made to analyze the supercritical power excursion initiated by a reactivity insertion at the rate of 100 $/s into a SFR, using the equations of state for pressure-energy density relationship e developed in this study for the single-phase liquid of U-Pu –Zr metal alloy. It was observed that the density-dependent equation of state used in this study predicted well the behavior of the pressure-density-energy of the core during the extreme power excursion. An effort should be made, however, to further investigate the validity of the equation of state at a high temperature and pressure above the critical point.

Acknowledgements

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