ANALYSIS OF STRESS IN REACTOR CORE VESSEL UNDER EFFECT OF PRESSURE LOSE SHOCK WAVE

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Abstract

High Temperature gas cooled Reactor (HTR-10) is a modular High Temperature gas cooled Reactor of the new generation. In order to analyze the safety characteristics of its core vessel in case of large rupture accident, the transient performance of its core vessel under the effect of pressure lose shock wave is studied, and the transient pressure difference between the two sides of the core vessel and the transient stresses in the core vessel is presented in this paper, these results can be used in the safety analysis and safety design of the core vessel of HTR-10.

Key Words: High Temperature Gas cooled Reactor Large Rupture Accident Pressure Lose Shock Wave Stress

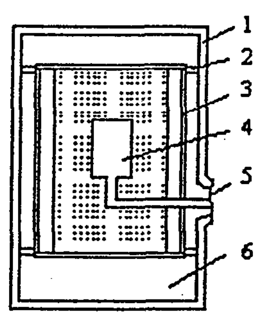
1 Preface

HTR-10 is a module High Temperature Gas cooled tested Reactor designed by institute of Nuclear Energy Technology (INET). Its double ends of the heat duct break accident is one of hypothesis ultimate accidents. The helium in the primary loop will jet from the rupture. When the accident happens and the heavily pressure loss shock wave are rapidly spread into the core. The safe characters of the core vessel in the shock wave define the safe stability of the structure component sin the core because the structure components are contained in the vessel of the core. So it is important to analyze the dynamic behavior of the vessel in the shock wave.

2 Simplified calculating model

Because the structure of the reactor core is very complex, we have several simplified hypothesises below.

The pebble-bed core is a simple gas cavity, and the effect of the coolant channel of the helium is ignored. Because the pressure drop in the core is spread around through gap of the coolant among the graphite components, we assumed the drop reach the inner wall of the core in a instant and the Graphite components are ideal rigid media in order to analyze the core vessel. In order to simplify the calculated region, the pressure vessel was dealt with as a cylinder vessel and the components on its top and bottom were neglected. The simplified analyzing model of reactor of HTR-10 is shown in figure 1. The component 3 is the core vessel which is cylinder shape, 0.30 meter thick, 6.3 meter high and mean diameter 3.8 meter in the figure. We can consider it as a shell because its thickness is much smaller than its height and diameter.



1. Vessel shell 2. Position pad 3. Core shell 4. Core 5. The rupture 6. Gas plenum

Figure 1. Simple model of HTR-10

3 mathematical model

We deal with the core shell in columnar coordinate(r, Φ, Z). The value of radius r is a constant "a" equaling the central radius of the cylinder shell.

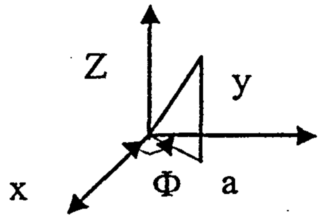
3.1 fluid region

3.1.1 Control equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0$$

$$\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U}\vec{U}) = -\nabla p$$

$$\frac{\partial \rho I}{\partial t} + \vec{U} \cdot \nabla (\rho I \vec{U}) = -p \nabla \cdot \vec{U}$$



$p=\rho RT$

$I=C_v T$

3.1.2 Boundary conditions

The boundaries of fluid are classified to four categories as follows:

(1) No sliding rigid wall

(2) Free sliding rigid wall

(3) Determined outflow

(4) Determined inflow

3.2 Solid region

3.2.1 Three dimensions elasticity shell equations

$$\rho h \ddot{U} = N_\phi^{\bullet} + N'_{\phi z} - M_\phi^{\bullet} / a + M'_{z\phi} / a$$

$$\rho h \ddot{V} = N'_z + N_{\phi z}^{\bullet}$$

$$\rho h \ddot{W} = q - M''_z + 2M_{z\phi}^{\bullet\prime} - M_\phi^{\bullet\bullet} - N_\phi / a$$

$$N_z = C(V' + \nu U^{\circ} + \nu W/a) \qquad N_\phi = C(U^{\circ} + W/a + \nu V')$$

$$N_{\phi z} = C(1-\nu)(V^{\circ} + U')/2 \qquad M_z = D(W'' + \nu W^{\circ\circ} - \nu U^{\circ}/a)$$

$$M_\phi = D(W^{\circ\circ} + \nu W'' - U^{\circ}/a) \qquad M_{z\phi} = -D(1-\nu)(W^{\circ\prime} - U'/a)$$

$C=E\bullet h/(1-\nu^2)$ $\qquad$ $D=E\bullet h^3/12(1-\nu^2)$

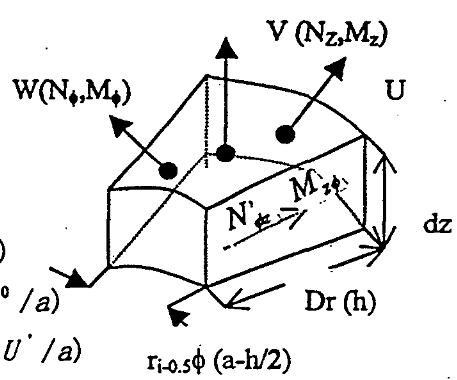


Figure 2 Control volume of fluid

3.2.2 The stress relations

The stresses are determined by the force and torque per length along the thickness of the vessel.

$$\sigma_{zm} = N_z / h \qquad \sigma_{zb} = 6M_z / h^2$$

$$\sigma_{\phi m} = N_\phi / h \qquad \sigma_{\phi b} = 6M_\phi / h^2$$

$$\sigma_{\phi zm} = N_{\phi z} / h \qquad \sigma_{z\phi b} = 6M_{z\phi} / h^2$$

3.2.3 Boundary conditions

Both ends of the core vessel are considered as fixed boundaries, so,

U=V=W=W' =0

3.3 Pipe region

3.3.1 In this code, we use one dimension control volume and its control equations are:

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial \rho u A}{\partial x} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{f}{2D}u^2 - \frac{k}{2L}u^2$$

$$\frac{\partial I}{\partial t} + u\frac{\partial I}{\partial x} = H_{fric}$$

$I=C_v T$

$p=\rho RT$

3.3.2 Boundary conditions

The boundary of the upper reach is the thermodynamic condition of the juncture unit of the vessel and pipe. The last expanded unit is surrounding atmosphere. The pressure of surrounding is the boundary of the lower reach.

4 Numerical method

The codes, K-FIX and FLX in this paper were designed by Los Alamos National Science Lab in U.S.A. K-FIX is composite of two parts and a two phases fluid dynamic code. FLX code is used in structure dynamic calculation, specially, study of the dynamic behavior of the supporting ring. The codes were redesigned by our institute (INET), and applied in the investigation of HTR. The figure 2 shows the control volume of fluid (solid shell).The calculation region and grid are shown in figure 3,4,5.

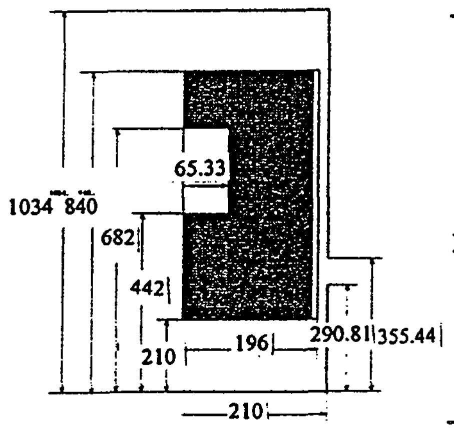


Figure 3 calculation region

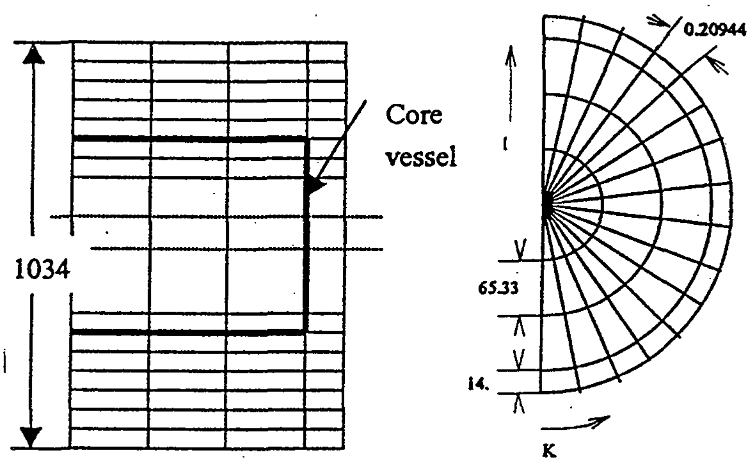


Figure 4 calculation grid for core

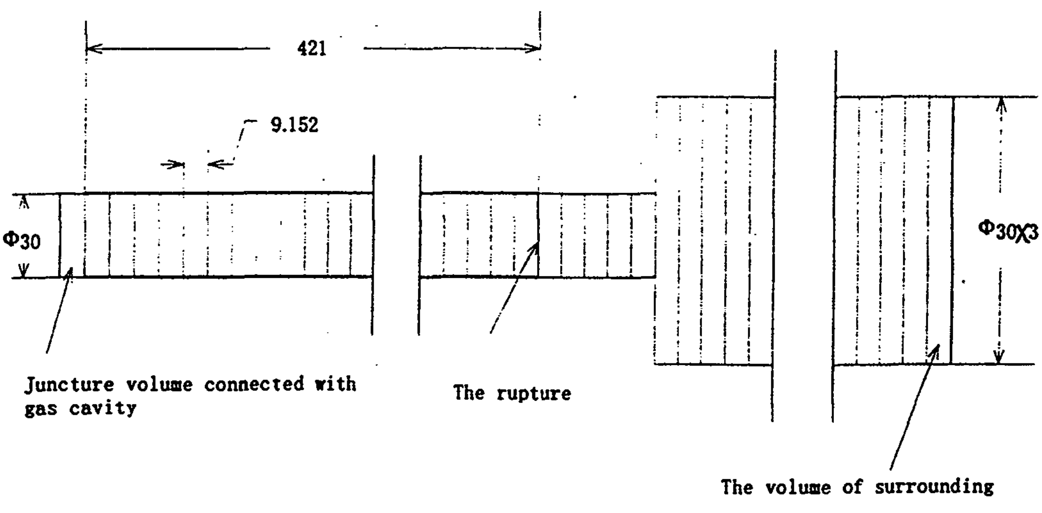


Figure 5 Pipe calculation grid

4.1 Fluid equations

The difference equations are solved through the point-relaxing method. First, the momentum equation (ignoring pressure item) is calculated to get the approximate velocity vector; then the continuity, momentum and energy equations are done by using the similar value for resulting in the exact velocity field. Whether or not the equations converge is controlled by the remaining of the continue equation. All iteration progresses are proceeded by the regulating pressure, calculating point by point till all points approach the exact results. At last, for getting the gas energy, the exact velocity will be put in the energy equation.

4.2 Solid equations

The equations are solved by the difference method, and the numeric results are reached through explicit integrating of limited difference equations. First, we used the displacements of the last step to calculate the force and torque per length, then we got the accelerate velocity in all direction that will be integrated to become new velocities and displacements. The next calculating step will go on.

4.3 Coupling of solid and fluid

The fluid code and solid code are coupled explicitly. In every iteration, the fluid pressures decide the distribution of pressure difference between one side and the other of the solid structure. The motion of the core vessel is driven by the accelerate velocity (force) in radius direction. And in the next step, new fluid pressure is decided, using the radius direction motion of the shell.

5 Results and analysis

We calculated the mechanic performance of the shell based on the simple core model of HTR-10. Results show that the eruption lasts no more than 1s. Within 2ms after the eruption, the pressure difference between inner side and outer of the core vessel rapidly goes up to 1.81Mpa. after 2ms, the pressure in the rupture and the pressure difference will go down slowly. The instant change of the pressure difference is shown in figure 6. The time axes is logarithm coordination. The distortion and stress of the core vessel near the rupture is lager than far from it. We choose the point of the largest stress near the rupture and calculate its stress. Its sum stress (the sum of membrane and bend stress) is respectively shown in figure 7,8,9. In this paper, we set the pull stress positive and press negative. The stress of any position in the thick section of the core vessel is the sum of membrane and bend stress.

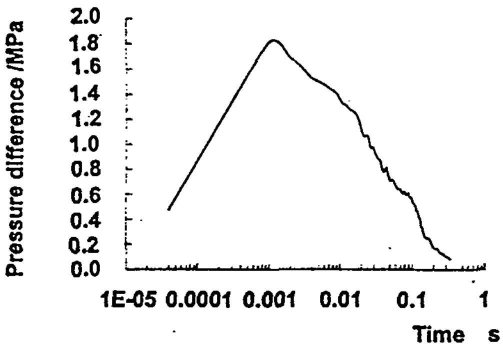


Figure 6 The rate of pressure difference between inner and outer side of the core vessel

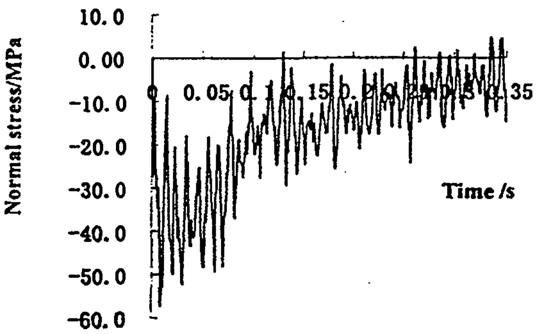


Figure 7 Normal stress in the axial section

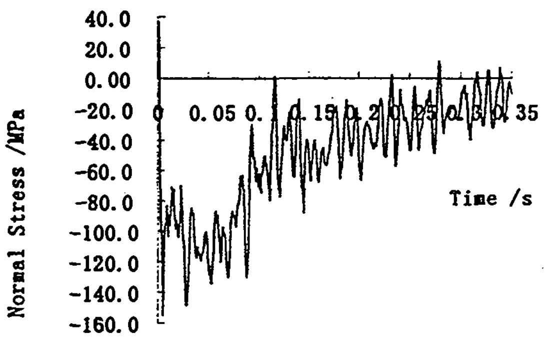


Figure 8 Normal stress in the peripheral section

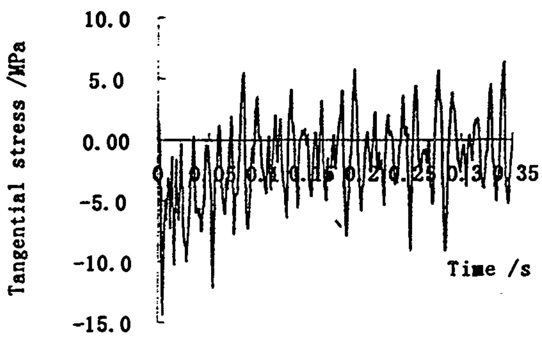


Figure 9 Tangential stress in the peripheral section

We can find that absolute normal stress in the peripheral section is the largest one, 100MPa order. It accords with the behavior of HTR under this kind of accident. Because of the chose point, which has the maximum stress, this point is the most dangerous one. As shown in figure. 7,8,9, the stress occurs while the helium goes out. After this, the altitude of the stress gradually decreases down to 0. Furthermore, when the double ends break accident occurs, it might damage the core, so strength of the shell must be checked. From the results, we can find that the maximum difference pressure between inner side and outer is 1.86MPa under the shock wave in the accident of the core vessel. The normal stress of the vessel in the axial section is 57MPa. The stress in the peripheral section is 158MPa, and the maximum tangential stress is 14.5MPa.

The material made of the core vessel of HTR-10 is 15CrMn and its yielding stress is bigger than 266Mpa at 255℃ in the accident. The calculating results show that the most dangerous point in the peripheral section has the maximum normal stress, about 15MPa. This value is smaller than 226MPa. According to the third strength theory[4]:

$$\bar{\sigma} = \sqrt{\sigma^2 + 4\tau^2} = \sqrt{158^2 + 4 \times 14.9^2} = 161 MPa < 226 MPa.$$

We can conclude that the core shell will not be destroyed and unstabilized. It is safe.

6 conclusion

High Temperature Gas cooled Reactor (HTR-10) is a modular High Temperature gas cooled Reactor of the new generation. It is designed and developed by INET, Tsinghua University. The double ends break accident of the heat gas duct is the most severe accident assumed. The safety character in the accident is important to the development of HTR. It is shown in the calculated outcomes. Even under this accident, HTR-10 still remains safe. HTR-10 has fine safety characters, at the same time, these data provide the basis to the core vessel analyzing and designing.

Symbol tabulation

U: Peripheral displacement (m);
V: Axial displacement (m);
W: Radius displacement (m);
ρ: Density (kg/m³);
h: Thickness of core vessel (m);
a: The central radius of the cylinder (m);
v: Poisson ratio;
q: The pressure difference of the inner and outer side of the vessel (Pa);
E: Yang modulus (Pa);
N: The force acting on the microelement of the vessel (N);
M: The torque acting on the microelement of the vessel (N•m);
I: Internal energy;
P: Gas pressure (Pa);
R: Gas constant;
T: Gas temperature (K);
C_v: Specific heat (J/kg);
H_{fric}: Dissipation of energy (J);
σ: Shell stress (Pa);
Subscripts:
' : Derivative of valuable with respect to z;
° : Derivative of valuable with respect to aϕ;
, : Derivative of valuable with respect to t;
Subscripts:
Z: Part of the valuable in Z direction;
Φ: Part of the valuable in aΦ direction ;
m: Menbrane stress;
b: bend stress;

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