DYNAMIC TRANSIENT ANALYSIS OF THE REACTOR CORE BARREL DUE TO SUDDEN RUPTURE OF THE RECIRCULATION LINE PIPING

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We have analyzed sudden rupture of the primary cooling loop which causes a water hammer event for the reactor core barrel. Assuming that core barrel is a thin shell, we have performed dynamic stress and strain calculations in the frequency domain. The Duhamel integral was used to calculate the transient response of a shell to an impulse load caused by the water hammer event. The results obtained were used to estimate structural stability of the core barrel.

A Recirculation Line Break (RLB) is a design basis Loss of Coolant Accident (LOCA) event that must be considered for stress analyses of Pressurized Water Reactors (PWR) [1-3] and Boiling Water Reactors (BWR) [4-5]. For the VVER (Soviet type of PWR reactor) the Recirculation Line Break is called in PNAE G-7-002-86 the "Maximum Design Accident". It is a severe accident scenario and is a significant source of dynamic loads on the reactor facility and building [4]:

- acoustic loads;
- drag force;
- annulus pressurization;
- jet impingements;
- pipe whip.

In current paper we will focus on the acoustic loads, which cause a water hammer type event on the reactor core barrel. When the decompression wave reaches the core barrel, the conditions of equilibrium of forces becomes broken, resulting in a significant dynamic force.

Preliminary calculations were performed in a static approach with use of a dynamic load factor equal to two, which is considered to be a conservative assumption. As a result of the calculation we find that core barrel stresses exceed the strength limit of the material. For more accurate results, we calculated behavior of the core barrel during the water hummer event using a dynamic approach. We perform calculations using analytical methods of analysis in the frequency domain. Thus we have to obtain natural asymmetrical shell frequencies of the core barrel. Then using mode expansion of applied water hammer load and the Duhamel integral we can obtain the resulting motion of a shell in response to the dynamic load, and calculate the membrane and bending stresses. Brittle strength can be estimated according to weight functions found in the literature [6].

1. Load definition

In recent years' numerous studies have been published which address the calculation and schematization of the acoustic loads with the aim of obtaining of accurate structural response of BWR internals [4]. The acoustic load amplitude and spatial distribution is itself a complex problem and is beyond the scope of the current work. We used a simple force approximation in the present study, and hope to address the problem of spatial load distribution later in a future study.

The initial condition considered for the water hammer event is: hot leg temperature 320ºC, cold leg temperature 290 ºC and pressure 16 MPa. Once the wave of depression reaches the core barrel, the unbalanced dynamic force appears in the form of pressure inside the barrel. Over time, the propagation wave reaches the opposite nozzle, dynamic forces repeatedly decrease. Therefore, the most important time period is the first few milliseconds of the water hammer event. We conservatively assume an instantaneous pipe break which causes a sudden force to be applied on an area equal to the inner diameter of the main cooling pipe (MCP) and is valid for the time required for the decompression wave to reach the opposite nozzle. Thus, this time is a half length of core barrel perimeter divided by the speed of sound (970 m/s) in water, which is equal to 6,5 ms. Schematization of the force is shown on fig.1.

In first time step 0…1 ms pressure drops to Riemann decompression value [4], this value is lower than the fluid saturation pressure (6.19 MPa). On the next time step 1…6.5 ms The break plane pressure remains at or near the Riemann decompression value until the fluid flashes to steam.

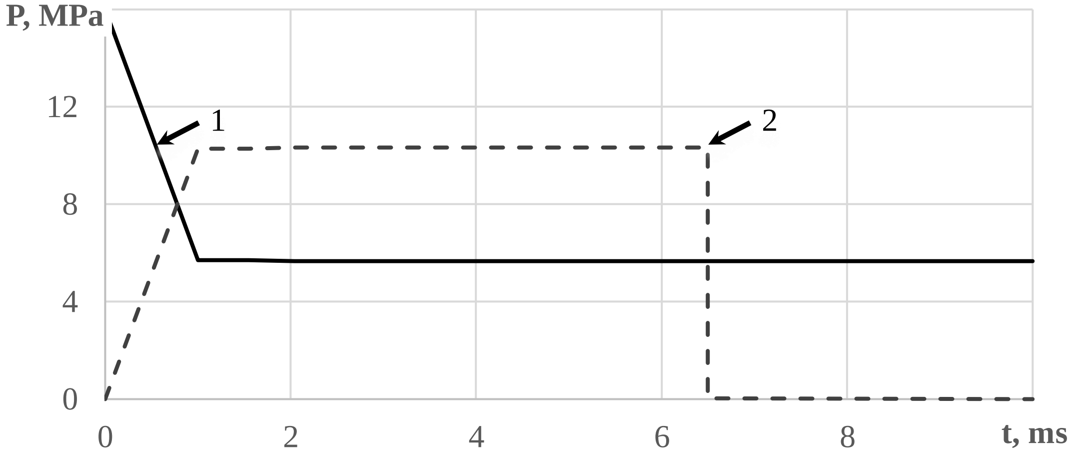

FIG. 1. Water hammer load schematization: 1 – pressure in cold leg, 2 – unbalanced pressure inside the Core Barrel.

2. Assessment of the core barrel shell behavior

Accounting for external pressure, the equation of motion can be obtained from the well-known equations of shell theory [7, 8]:

$$\frac{\partial^2 N_x}{\partial x^2}-\frac{1}{R}\frac{\partial^3 Q_x}{\partial\varphi^2\partial x}-\frac{1}{R^2}\frac{\partial Q_\varphi}{\partial\varphi}-\frac{1}{R^2}\frac{\partial^3 Q_\varphi}{\partial\varphi}-\frac{\rho h}{R}\left(\frac{\partial^3 v}{\partial\varphi\partial t^2}-\frac{\partial^4 w}{\partial\varphi^2\partial t^2}-\frac{\partial^4 u}{\partial x^2\partial t^2}R\right)=-\frac{\partial^3 P}{\partial\varphi^3}. \qquad (1)$$

First of all we will solve the problem of shell natural frequencies, thus external pressure is neglected in eq.(1). According to Vlasov hypotheses[8]:

$$\left(\frac{\partial v}{\partial\varphi}+w\right)<<w,v \quad \text{and} \quad \left(\frac{\partial u}{R\partial\varphi}+\frac{\partial x}{\partial x}\right)<<w,v\,, \qquad (1)$$

geometrical equations,eq.(1) can beexpressed in terms of the tangential displacements v. Assuming that displacements v could be expanded as $v(x,\varphi,t)=\Psi(x)\cdot\sin(n\varphi)\sin(\omega t)$ equation (1) can be rewritten as 4th order ODE:

$$\frac{d^4\Psi(x)}{dx^4}+2A\frac{d^2\Psi(x)}{dx^2}-B\Psi(x)=0 \text{ ,where}$$

$$A=\frac{1}{R^2}\frac{-n^6+n^4-\dfrac{n^2(1-\mu)}{4}+\dfrac{\rho hR^4\omega^2}{D}}{n^4+\dfrac{EhR^2}{D}} \quad B=\frac{1}{R^4}\frac{\dfrac{\rho hR^4\omega^2}{D}n^2\left(n^2+1\right)-n^4\left(n^2-1\right)^2}{n^4+\dfrac{EhR^2}{D}} \qquad (2)$$

The eq.(2) solution is expressed:

$$\Psi(x)=C_1\cos(\lambda_1 x)+C_2\sin(\lambda_1 x)+C_3\cosh(\lambda_2 x)+C_4\sinh(\lambda_2 x) \qquad (3)$$

We have used notations C_1, C_2, C_3, C_4 – arbitrary constants defined from boundary conditions:on the upper boundary $w(0)=0$ and $M_x(0)=0$,on the bottom boundary $w(l)=0$ and $\gamma(l)=0$.

The solution of nonlinear equation (3) can be written in explicit form:

$$\omega_{n,k}=\sqrt{\frac{\left(\frac{ER^2h}{D}+n^4\right)\left(\frac{4m+1}{4}\pi\frac{R}{L}\right)^4+\left(\frac{4m+1}{4}\pi\frac{R}{L}\right)^2\left(2n^4-2n^2+\frac{1-\mu}{2}\right)n^2+n^4\left(n^2-1\right)^2}{\frac{\rho R^4h}{D}\left[\left(\frac{4m+1}{4}\pi\frac{R}{L}\right)^2+n^2\left(n^2+1\right)\right]}} \quad (4)$$

The roots of this non linear equation give us asymmetrical natural frequencies of the reactor core barrel. For the purpose of our analysis we will consider several lowest frequencies.

In order to find dynamic response,tangential displacement could be expanded as $v(x,\varphi,t,n,k)=\Psi(x)\cdot\sin(n\varphi)f(t)$.

Function $\Psi(x)$ is already found (see eq.(3)), then eq.(1) could be rewritten as:

$$\ddot{f}(t)\Psi(x)\sin(n\varphi)+\omega^2 f(t)\Psi(x)\sin(n\varphi)=-\frac{1}{\rho hn^2\left(n^2+1\right)}\frac{\partial^3 P}{\partial\varphi^3}. \quad (5)$$

External pressure $P(x,\varphi)=\sum_n\sum_k A_{n,k}\Psi(x)\cos(n\varphi)$ could be expanded using vibration modes. Where $A_{n,k}$ are unknown coefficients defined by:

$$A_{n,k}=\frac{\int_0^l\int_0^{2\pi}P(x,\varphi)\Psi(x)\cos(n\varphi)d\varphi dx}{\int_0^l\int_0^{2\pi}\Psi^2(x)\cos^2(n\varphi)d\varphi dx}. \quad (6)$$

Using this expansion we can rewrite eq.(5):

$$\ddot{f}(t)+\omega_{n,k}{}^2 f(t)=-\frac{n}{\rho h\left(n^2+1\right)}A_{n,k}P(t). \quad (7)$$

Eq.(7) is solved using Duhamel integral, Thus all the components of $v(x,\varphi,t)$ are defined, and we can find other displacements:

$$w(x,\varphi,t,n,k)=-\Psi(x)\cdot n\cos(n\varphi)f(t) \quad \text{and} \quad u(x,\varphi,t,n,k)=R\cdot\Psi'(x)\cdot\frac{\cos(n\varphi)}{n}f(t) \quad (8)$$

These displacements allow us to compute all components: forces, strains, curvatures defined. as sums of all modes. Calculations are performed for two points:

- A - Location of water hammer load, the point of maximum stress;
- B - Center of Active Zone, the point of maximum material degradation.

According to results, the maximum bending stresses are 550 MPa, a relatively high value, which should be used only in fracture analysis, as far as it is obtained for short dynamic impulse.

Brittle strength is estimated for postulated cracks in two zones:of maximum stresses – point A and of maximum material degradation, due to the neutron irradiation – point B.

Postulated cracks have dimensions according to PNAE G-7-002-86:*a = 0,25h, a/c = 0.3*. We consider two types of cracks: axial and circumferential, on the internal and external surfaces of the core barrel, separately.

For an axial crack [10, 11] the Stress Intensity Factor (SIF) is given by:

$$K_1=\sigma_j\sqrt{\frac{\pi a}{Q}}G_j\left(\frac{a}{c},\frac{a}{h},\frac{h}{R},\phi\right),\ \sigma_j=\left(\frac{z}{h}\right)^j \quad j=0,1,2,3 \quad (9)$$

$Q=1+1.464(a/c)^{1.65}$ - elliptic integral of second type, $G_j\left(\frac{a}{c},\frac{a}{h},\frac{h}{R},\phi\right)$ coefficients taken from [6]

The SIF for a circumferential crack is given by:

$$K_1 = \sigma_j \sqrt{\pi a} f_j\left(\frac{a}{c}, \frac{a}{h}, \frac{h}{R}, \phi\right), \; f_j = A_j\left(\frac{2\phi}{\pi}\right)^j \quad j = 0,1,2,3,4,5,6 \tag{10}$$

Coefficients A_j are taken from [9].

The core barrel material is Stainless Steel Type 321 (X6CrNiTi18-10S), andthe neutron irradiation is approximately 0.09 dpa/year; therefore, its mechanical properties have slight degradation [10]. The most dangerous orientation is an axial external crackK_I=99.401MPa√m. Because we consider short term dynamic impact, we might better use K_{ID} which is about 0.7K_{IC}. In this case brittle strength criterion is also satisfied.

3. Conclusions

In this article we have built the model of reactor core barrel under assumptions of Vlasov's semi-momentless theory. The dynamic response was obtained for the short term impulse loading.

Calculations of stress distribution were performed over the height and circumference of the core barrel. The following conclusions can be drawn on the base of calculation results:

i. shell movement of the core barrel doesn't cover the annulus between the pressure vessel and core barrel, i.e cooling of the active zone will be held according to the planned scenario;

ii. under dynamic loads the fracture behavior changes from ductile to brittle, so brittle strength is of a great importance. Terms of brittle strength for all the postulated cracks in the core barrel performed with an essential margin.

Although we have used simplified force schematization and assumptions of Vlasov's semi-momentless theory, these results provide useful insight into response of the system. This work represents an initial investigation into the event and the further study can address more realistic force determination.

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