Asian Nuclear Prospects 2012
(ANUP2012)

Analysis on Dropping Accidents of Fresh Fuel Cask in HTGR

NIE Junfeng *, ZHANG Haiquan, LI Hongke, WANG Xin, ZHANG Zhengming

Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, 100084, China

Abstract

The fuel of HTGR is made of some spherical fuel elements with diameter of 60mm. The cask of fresh fuel is used to temporarily store and transport such a kind of new spherical fuel elements, and it may drop during transport. The dropping process can be simulated by two ways. The first is the coupled Euler-Lagrange (CEL) method, in which the new fuel elements are taking as fluid and can be considered explicitly. The second is referred to as the equivalent mass method. In the method, the cask and the new fuel are not considered individually, and the mass of the new fuel elements is averagely allocated to the bottom head of the cask. The simulating result shows that the CEL method can describe the flow and inertial effects of the new fuel elements in the dropping process, and the lateral fluid dynamic pressure generated by fuel elements to the cask. The impact effect can be fully considered in the equivalent mass method. Results show that the impact force is stronger and the contact time is shorter than that of the CEL method. Finally, parameters of equivalent fluid in the CEL method are discussed. And the results show that the fluid model is reasonable. In one word, calculation results of the two methods can be combined in structural design, which will give a more reasonable design.

1. Background

The fuel elements of HTGR are sphere, and the diameter is 60 mm[1]. The fuel elements need to be stored and shipped temporarily by special casks[2, 3]. There are thousands of fuel elements in a cask.

* Corresponding author. Tel.: +86010-62788595-818; fax: +86010-62795146.
E-mail address: niejf@tsinghua.edu.cn.

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Selection and peer-review under responsibility of Institute of Nuclear and New Energy Technology, Tsinghua University

Keywords: cask of new fuel, dropping accident, CEL, equivalent mass method, FEM
Because of the liquidity of the fuel elements, they exert lateral pressure to the cask wall. Especially in a dropping accident, inertia, liquidity and lateral pressure of the fuel elements can’t be neglected.

Dropping of casks needs detailed stress analysis and safety evaluation for the cask. According to the IAEA Safety Standards Series—"Advisory material for the IAEA regulations for the safe transport of radioactive material" [4], which was published at 2002, the integrity and safety evaluation of the cask used for transportation and storage of nuclear fuel elements need to do drop test and penetrate test with different height. However, there is no specific standard to evaluate dropping accidents of the fuel cask in HTGR. The analysis method of dropping accidents of the fuel cask should include liquidity analysis of the fuel elements, but there are no reports in the literature on how to deal with the fuel element effects on the cask either. Consideration of hydrodynamic pressure of the fluid-filled cask is also needed. And the main methods are Add Mass Method [5], FEM [6, 7], and SPH [8], which can be used as reference for this problem.

There are nonlinear, large deformation and transient impact in dropping accidents of the new fuel cask in HTGR. The fuel elements have liquidity, which can generate lateral pressure to the wall of the cask. In this paper, the commercial FE software ABAQUS [9] is used to research the dynamic response of the fuel cask in the dropping process. Both the coupled Euler-Lagrange (CEL) method and the equivalent mass method are used to simulate the effect of the spherical fuel elements on the cask. This paper can be used as reference for analysis of similar accidents and design of corresponding structures.

2. Introduction for the simulation method

The key problem is how to simulate the spherical fuel elements of the cask. According to the research on the reactor core of pebble-bed, the gravity of the pebble-bed will generate pressure on the reactor wall. And it is similar to hydrostatic pressure within a certain range. If the depth of the pebble-bed is less than 4 meters, the pressure generated by the spherical fuel elements can be described by the following formula:

\[ P = \gamma (1 - \varepsilon)H \]  

In which, \( \gamma \) is the density of the fuel elements, \( \varepsilon \) is the porosity of the pebble-bed, and \( H \) is the depth of the pebble-bed. But when the depth becomes larger, the increasing pressure is offset by the friction between the fuel elements and the cask wall. And the pressure is close to an equilibrium value of 0.04MPa (0.4 times the atmosphere pressure).

For this reason, in order to consider the inertia during the dropping process and the lateral pressure on the cask wall, the fuel elements in the cask can be treated as equivalent liquid for considerations of fluidity. The model can be simulated by the solid-fluid couple algorithm of the FEA software. It can describe the fluidity of the fuel elements and the lateral pressure on the cask.

The commercial FE software ABAQUS/Explicit contains Eulerian algorithm, which can simulate the behavior of liquid based on VOF (volume-of-fluid) method. It can describe morphology and distribution at any point by calculating EVF (Eulerian volume fraction) of the mesh elements all over the material. Furthermore, the interaction between the Eulerian material and the Lagrangian element can be described by the Eulerian-Lagrangian contact algorithm, so it can simulate the completely Lagrangian coupled problem of solid-fluid structures [10].

There are some important material parameters in CEL method: equivalent density \( \rho \) (kg/m³), Equation of State (EOS) parameter \( c_0 \) (m/s), and viscosity coefficient \( \eta \) (Pa·s). In order to be consistent with other units in the simulation process, the units of density, EOS parameter and the viscosity coefficient are t/mm³, mm/s, and MPa·s, respectively.

3. FEM model

3.1. Geometric model
For simplicity, the cask model is a cylinder container with a spherical head. The height of the cylinder is 2000 mm, the diameter is 1000 mm, and the thickness is 15 mm. The fuel elements occupy 90% of the volume of the cask. The FEM model of the cask is showed in Fig. 1.

In order to describe the movement of fuel elements during dropping process of the cask, an equivalent liquid model of CEL algorithm is established. Mesh dividing of FEM model is showed in Fig. 2. Equivalent liquid is described as Eulerian mesh, and the cask is described as Lagrangian mesh. The mesh of rectangular section in Fig. 2 is spatial Eulerian mesh. The grey part in the middle is full of liquid, and the black part around it is empty of liquid. The space Eulerian mesh need to be larger than the space occupied by the liquid at the initial state, because the cask and the liquid will deform in the subsequent dropping process.
3.2. The parameters of material

The material of the cask is stainless 304L, and properties of the material are from ASME Boiler and Pressure Vessel Code, Section II, Material Specifications, Part D Properties \[11\]. The yield strength is 177MPa, tensile strength is 480MPa, and elongation is 40%.

We can get the equivalent density from mass and volume of the fuel elements in the cask. And it is \(1.04 \times 10^{-9} \text{ t/mm}^3\). The EOS parameter reflects the compressibility. Equivalent liquid is considered as incompressibility in this problem. We assume that the EOS parameter is \(c_0 = 1500 \text{ m/s}\), and the viscosity coefficient is \(\eta = 1.0 \times 10^{-9} \text{MPa} \cdot \text{s}\).

3.3. Boundary condition

Generally for cask fall, two modes are considered, vertical drop and corner drop. This paper covers only vertical fall. In our case, the fuel cask drops from 9 meters’ high to a rigid ground, so the velocity of the fuel cask is about 13.3 m/s just before it impacts to the ground. Because it is a transient dynamic problem, so it can be solved by ABAQUS/Explicit model \[12\]. The interaction between the fuel elements and the cask is described by the couple solid-fluid algorithm, and the interaction between the cask and the ground is described by the explicit contact algorithm.

4. The results and discussion

4.1. The results of the CEL method

![Fig. 3 Vertical displacement-time curve of the fuel cask during dropping simulated by CEL method (U_2 is the vertical displacement)](image)

After the cask hit the ground, it changed its state from falling to rebounding. As a result of the CEL simulation, the vertical displacement - time curve of the node on the cask wall is showed in Fig. 3, which describes the dropping process of the cask. The duration between the time when the cask just touched the
ground and the time when it began to rebound is 4.5 ms. The maximum vertical displacement of the cask after it touched the ground is 19.9 mm. And then the cask began to rebound. The radial deformation – time curve calculated by CEL method is showed in Fig. 4, which shows that the maximum deformation of the cask is about 36.5 mm. This result shows the obvious lateral expansion of the cask, and the point with the maximum deformation is at the bottom of the cask wall.

Comparison Fig.3 with Fig.4, we can find that when the cask had the maximum vertical displacement, the radial deformation reached the maximum value at the same time. Mises stress also reached the maximum value at 192.3MPa. The part with the maximum Mises stress is the same as that with the maximum radial deformation, which is showed in Fig.5. In the same situation, the deformation reached the most serious condition. And the contour of deformation at 4.5ms is showed in Fig. 6.

![Fig. 4 Radial deformation-time curve of the fuel cask during dropping simulated by CEL method (U_r is the radial deformation)](image)

![Fig. 5 Mises stress contour of the fuel cask simulated by CEL method](image)
4.2. The results of the equivalent mass method

The equivalent mass method does not consider the cask and the fuel elements individually, and the mass of the fuel elements is equally distributed to the bottom of the cask. In other word, considering the mass of the fuel elements, method of equivalent density is adopted for the head at the bottom of the cask.

The vertical displacement - time curve calculated by equivalent mass method is showed in Fig. 7. The duration between the time when the cask just touched the ground and the time when it began to rebound is 0.85ms. The maximum vertical displacement of the cask after it touched the ground is 4.4mm. And then
the cask began to rebound. The radial deformation – time curve calculated by equivalent mass method is showed in Fig. 8. The maximum lateral deformation of the cask is about 8.0 mm, which is much smaller than that of CEL method. It means that the equivalent mass method can’t capture the lateral deformation very well.

The contour of Mises stress simulated by the equivalent mass method is showed in Fig. 9. It shows that the maximum Mises stress is 214.4MPa. At the same time, the deformation reached the most serious condition. And the contour of deformation at 0.85ms is showed in Fig. 10. The point with the maximum value of Mises stress is the same as that in CEL method. But the maximum Mises stress value is larger than that in CEL method.

![Fig. 8 Radial deformation -time curve of the fuel cask during dropping simulated by equivalent mass method. (U_r is the radial deformation)](image)

![Fig. 9 Mises stress contour of the fuel cask simulated by equivalent mass method](image)
4.3. Comparison of the two simulation methods

Compared with the results of the equivalent mass method, the results of CEL method have many characteristics. Contact time between the cask and the ground is longer, impact force is weaker, and Mises stress is smaller. The reason is that the CEL method can consider the inertia of the fuel elements, so there is a buffering effect and a delayed action in the dropping process. On the contrary, all of the mass of fuel elements are concentrated on the bottom head of the cask in equivalent mass method. There is no relative motion between the fuel elements and the cask. As a result, there is no buffering effect, and the impact force is much stronger.

The radial deformation of CEL method is 4 times that of the equivalent mass method. The result shows that the lateral pressure and the inertial effect of the fuel elements are important factors for radial deformation of the cask.

In short, the equivalent mass method can include the impact effect sufficiently, but the CEL method can reflect the lateral pressure and inertial effect of the fuel elements. It is deduced that the actual dropping accident will be between the two models.

4.4. Discussion on the parameters of the CEL method

The parameters of the CEL model are very important for the result, so reasonableness of the parameters needs to be discussed. Firstly, the equivalent density of the fuel elements is calculated from the total mass and volume of the fuel elements, and the result is 1.04 t/mm³. Secondly, the EOS parameter reflects the compressibility of the volume, and it is equal to bulk modulus in the case of small deformation. In a slow impact, equivalent liquid can be considered as incompressible, and the EOS parameter is 1500 m/s.

Finally, in order to determine the coefficient of viscosity, values from $1.0 \times 10^{-9}$ to $1.0 \times 10^{-1}$ MPa·s were tested. The relationship between the quantity and the coefficient of viscosity is shown in Fig. 11 and Fig. 12. They are the maximum radial deformation – coefficient of viscosity curve and the maximum duration of contact time – coefficient viscosity curve, respectively. Both of the curves show that the maximum
radial deformation and the maximum duration of contact time changes a little with the coefficient of viscosity increasing from $1.0 \times 10^{-9}$ to $1.0 \times 10^{-1}$ MPa\cdot s. Therefore, it can be deduced that $1.0 \times 10^{-9}$ MPa\cdot s is reasonable for the coefficient of viscosity in the CEL model.

![Fig. 11 The maximum radial deformation – coefficient of viscosity curve of CEL method](image1)

![Fig. 12 The maximum duration of contact time – coefficient of viscosity curve of CEL method](image2)

5. Conclusion

The dropping accident of the fuel cask is a complicated mechanics problem, and it is more complicated when fluidity and lateral pressure of the fuel elements are considered. In this paper, both the CEL method and the equivalent mass method are used to simulate the dropping accident of the new fuel cask. The results show that impact force is stronger and contact time is shorter in the equivalent mass method. But
the CEL method can describe the radial expansion of the cask. Therefore, the CEL method is able to simulate the inertial effects and liquid effects of the fuel elements, and the equivalent mass method can fully consider the impact effect. Calculation results of the two methods can be combined in structural design, which will give a more reasonable design. As a result, both of the two methods show that, though the maximum Mises stress of the cask exceed the yield stress of stainless 304L, it is far less than the tensile strength. So the cask integrity is maintained in the dropping accident from 9m high to a rigid ground.

References


