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Experimental and numerical investigation of sloshing behavior in annular region separated by several cylinders related to fast reactor design

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A R T I C L E I N F O

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A B S T R A C T

The liquid sloshing behavior analysis of reactor vessel is an important topic of sodium-cooled fast reactor design. It is known that there are two pumps and four heat exchangers immersed in sodium liquid. Although lots of research work has been performed on the liquid sloshing inside simple cylindrical tank and coaxial circular cylinders, few about sloshing inside annular region separated by several cylinders (ARSSC), this paper deals with the analysis of the liquid sloshing inside the ARSSC geometry. A simplified cylindrical tank of fast reactor was designed, in which there are six internal cylinders used to model pumps and heat exchangers. By shaking table experiments, the number of internal cylinders was gradually increased, and the natural frequency and wave height of liquid sloshing were measured under each case. In numerical investigation, the VOF models were built to record wave height using the CFD simulation approach, the conditions were consistent with experiments. Much different with previous research, the characteristics of sloshing inside ARSSC geometry were strongly dependent on the number of internal cylinders. Experiment results showed that the natural frequency and wave height all decrease with the increase of internal cylinders gradually. The wave height response obtained by numerical simulation was in good agreement with the experimental results. In addition, as the increase of internal cylinders gradually, the maximum sloshing response occurred when the forcing frequency matched high order natural frequency of sloshing. Moreover, a correction factor was obtained by experiments for the natural frequency theoretical calculation formula. The conclusions can provide favorable reference for the seismic design of the sodium-cooled fast reactor.

1. Introduction

Since the Fukushima nuclear accident in 2011, the safety of nuclear power plant under the seismic condition has become a case of major attention around the world. The reduction of damage to the reactor under seismic load has become the topic of the reactor structure design. Compared with pressurized water reactor, the operating parameters of sodium-cooled fast reactor(Yue et al., 2018) are characterized by low pressure and high temperature, and the fast reactor has the characteristics of large size and thin wall, so the stiffness of structure is relatively low (Hu and Chen, 2018). In the extreme condition, liquid sloshing inside the reactor vessel may introduce extra loads on the roof, internal components and vessel wall, these loads may endanger structural integrity under long-period seismic condition. For the safety assessment of fast reactor, it is necessary to consider the liquid sloshing behavior (Roesset, 1998).

Since the sloshing behavior is involved into a strongly nonlinear phenomenon, which will bring some difficulties to seismic response evaluation (Housner, 1957, 1963). In the present study, the methods of studying liquid sloshing can be divided into two categories: experimental methods and numerical investigation methods. Numerous experiment researches have been carried out on sloshing of standard annular region. A small scale experiment of sloshing considering the seismic safety of MYRRHA, has been presented by (Myrillas et al., 2016). Their study provided the qualitative results of the liquid sloshing motions inside the model with flow visualization. The pressure sensors were used to study liquid sloshing behavior, the experimental data were compared to the computed velocity and pressure by finite Volume of Fluid method, comprised an incompressible VOF method and a compressible VOF method (Lyu et al., 2017). In addition, extensive numerical study methods on liquid sloshing have been proposed, such as the Boundary Element Method (BEM) (Abbaspour and Hassanabad, 2009), the Finite Element Method (FEM) (Mitra et al., 2012), the Finite Difference Method (FDM) (Wu and Chen, 2009). In the calculation of

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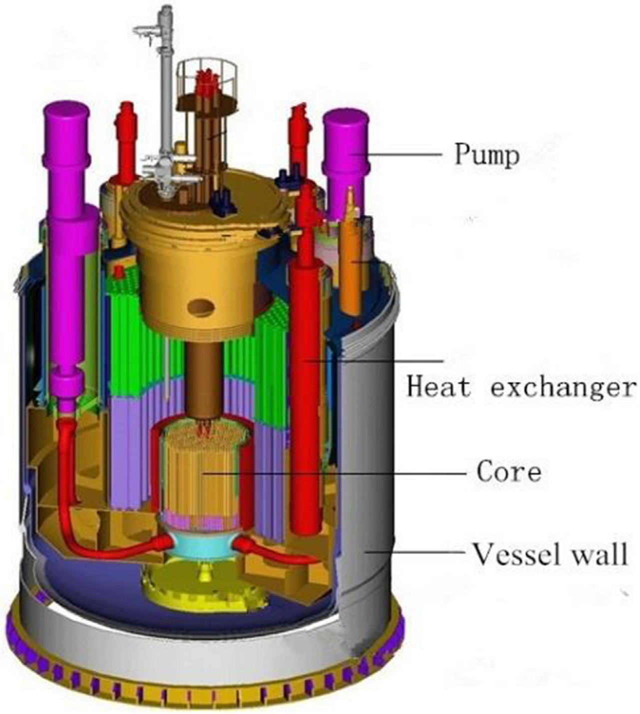

Fig. 1. The sodium-cooled fast reactor (ARSSC).

the sloshing wave by the mesh method, the Mark and Cell (MAC) method and the Volume of Fluid (VOF) method have been applied to capture the profile of the interface in liquid sloshing wave simulations (Lyu et al., 2017). Arai (Arai et al., 2002) used the MAC approach to simulate sloshing impact pressure. Hirt and Nicols firstly proposed the Volume of Fluid (VOF) method, in which the free surface was constructed by segments parallel to the coordinates, which was applied widely subsequently. Eswaran et al. (2009) proposed a numerical method based on Volume of Fluid (VOF) method with arbitrary-Lagrangian-Eulerian (ALE) formulation to study baffled and un-baffled tanks with a nonlinear sloshing behavior.

For the experimental investigation, liquid sloshing mode shape, natural frequency and wave height are important parameters in the measurement process. Although lots of research work has performed on the liquid sloshing inside simple cylindrical tank and standard annular region, few about sloshing inside annular region separated by several cylinders (ARSSC), shown in Fig. 1. There were two pumps and four heat exchangers in reactor vessel, this paper focus on the subject of the liquid sloshing inside the ARSSC geometry. To demonstrate the effect of the internal cylinders on the sloshing behavior, shaking table experiments using a simplified fast reactor model were carried out on experiments set-up, discussed in Section 3. The geometry of fast reactor was simplified to a cylindrical model, in which there were six internal cylinders used to simulate the two pumps and four heat exchangers. The number of internal cylinders was increased gradually, the sweep frequency and resonance excitation signal were applied to the shaking table for analyzing sloshing behavior. Numerically, the same test-cases were performed using CFD approach, presented in Section 4. Both the experiments and CFD simulations results are presented in Section 5, showing the change tendency of liquid natural sloshing frequency, mode shape and wave height with increasing the number of cylinders. Finally, the conclusions of liquid sloshing behavior analysis are drawn in Section 6.

2. Sloshing theory

So far, many scholars have carried out lots of theoretical research of liquid sloshing on standard annular region. The natural frequency and wave height calculation formula for a standard annular cylindrical tank have been obtained, these parameters are important parameters for studying liquid sloshing. Abramson (1966) applied the velocity potential theory to analyze the sloshing equation of the cylindrical tank. The sloshing natural frequency can be expressed by the following equation:

$$\omega_{mn}^2 = \left(\frac{g}{a}\right)\xi_{mn}\tanh\left(\xi_{mn}\frac{H}{a}\right) \tag{1}$$

where for antisymmetric mode $m = 1$: $\xi_1 = 1.46$, $\xi_2 = 5.66$, ω_{mn} is natural frequency, g the gravitational acceleration, a the outer radius of tank and H the liquid level.

It is well-known that the maximum sloshing response occurs at case of resonance, when the forcing frequency matches the natural frequency of sloshing. Liquid sloshing may jeopardize structural integrity in resonance case, so it is crucial to investigate this case. In this paper, three resonance sine waves signal were input to shaking table. If the shaking table was excited by sine wave with the sloshing natural frequency, the maximum wave height response was obtained by (Fujita et al., 1985) as the following equation:

$$\eta_{\max} = \frac{a}{g}Q_1G_1(a)3\pi D_g\omega_1^2 \tag{2}$$

where $\eta_{\max}$ is the maximum of wave height, D_g the amplitude of sine wave, $\omega_1 = 2\pi f$.

$$Q_1 = 2\left[\frac{2}{\pi\xi_1} - kG_1(b)\right]\Big/\left[\frac{4}{\pi^2}\xi_1^2(\xi_1^2-1) + G_1{}^2(b)(1-k^2\xi_1^2)\right] \tag{3}$$

$$G_1(a) = J_1(\xi_1)Y_1'(\xi_1) - J_1'(\xi_1)Y_1(\xi_1) \tag{4}$$

$$G_1(b) = J_1(\xi_1k)Y_1'(\xi_1) - J_1'(\xi_1)Y_1(\xi_1k) \tag{5}$$

where $k = b/a$, b is the inside radius of tank, $J_1(\xi_1)$ the Bessel Function of the First Kind, $Y_1(\xi_1)$ the Bessel Function of the Second Kind, $J_1'(\xi_1)$ the Differential of Bessel Function of the First Kind and $Y_1'(\xi_1)$ the Differential of Bessel Function of the Second Kind.

3. Experiments

In order to analyze the sloshing behavior of ARSSC geometry, a reduced scale fast reactor model was designed and the shaking table experiments were completed.

3.1. Scaling analysis

It is very difficult to carry out 1:1 model test for the large container of fast reactor. Therefore, it is necessary to carry out the reduced scale model test, the problem of similarity has to be respected. According to dimensional analysis by (Abramson, 1966), some main governing dimensionless numbers should be respected, which are as follows.

- Froude number: $Fr = \frac{V^2}{Lg}$
- Euler number: $Eu = \frac{P}{\rho_f V^2}$
- Reynolds number: $\mathrm{Re} = \frac{VL}{\nu}$
- Bond number: $Bo = \frac{\rho g L^2}{\sigma}$

where V represents the velocity, L the size of cylindrical model, P the pressure of liquid, ρ_f the density of fluid, ν the kinematic viscosity and σ the surface tension.

After analysis, the Froude number, Euler number, and Bond number should be respected and the Reynolds number is relaxed when ignoring viscosity effects. Finally, the scaling factors are gained and summarized in Table 1.