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CFD and experimental investigation of sloshing parameters for the safety assessment of HLM reactors

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HIGHLIGHTS

- Comparison of sloshing behavior in cylindrical tank using mercury and water.
- Flow visualization of liquid sloshing in resonance case.
- CFD simulations of sloshing with OpenFOAM, using the VOF method.
- Qualitative and quantitative comparison of experimental and numerical results.
- Evaluation of sloshing forces on the tank walls from numerical simulations.

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ABSTRACT

For the safety assessment of Heavy Liquid Metal nuclear reactors under seismic excitation, sloshing phenomena can be of great concern. The earthquake motions are transferred to the liquid coolant which oscillates inside the vessel, exerting additional forces on the walls and internal structures. The present study examines the case of MYRRHA, a multi-purpose experimental reactor with LBE as coolant, developed by SCK·CEN. The sloshing behavior of liquid metals is studied through a comparison between mercury and water in a cylindrical tank. Experimental investigation of sloshing is carried out using optical techniques with the shaking table facility SHAKESPEARE at the von Karman Institute. Emphasis is given on the resonance case, where maximum forces occur on the tank walls. The experimental cases are reproduced numerically with the CFD software OpenFOAM, using the VOF method to track the liquid interface. The non-linear nature of sloshing is observed through visualization, where swirling is shown in the resonance case. The complex behavior is well reproduced by the CFD simulations, providing good qualitative validation of the numerical tools. A quantitative comparison of the maximum liquid elevation inside the tank shows higher values for the liquid metal than for water. Some discrepancies are revealed in CFD results and the differences are quantified. From simulations it is verified that the forces scale with the density ratio, following similar evolution in time. Overall, water is demonstrated to be a valid option as a working liquid in order to evaluate the sloshing effects, for forcing frequencies up to resonance.

1. Introduction

Seismic safety of nuclear reactors is of primary importance and it has been brought to focus even more after the Fukushima I Nuclear Power Plant was struck by the violent (magnitude 9.0) Tōhoku earthquake and the resulting tsunami in March 2011. For a partially filled Heavy Liquid Metal (HLM) nuclear reactor under seismic excitation, large liquid motions, known as *sloshing*, can introduce extra loads on the structures and internal components (Thomas and et al., 1963). These loads are hard to predict because of the non-linear nature of sloshing, but prediction methods are necessary for the safety assessment. The present study refers to MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), which is a versatile experimental Accelerator-Driven System (ADS) under development at the SCK·CEN, the Belgian Nuclear Research Centre (Baeten et al., 2014). It is designed to use Lead–Bismuth–Eutectic (LBE) alloy as liquid coolant and a schematic is presented in Fig. 1.

The problem of sloshing has been studied extensively for many different applications, from aerospace and liquid transport to seismic safety of storage tanks and nuclear reactors (Ibrahim, 2005; Faltinsen and Timokha, 2009). Guidelines for the seismic

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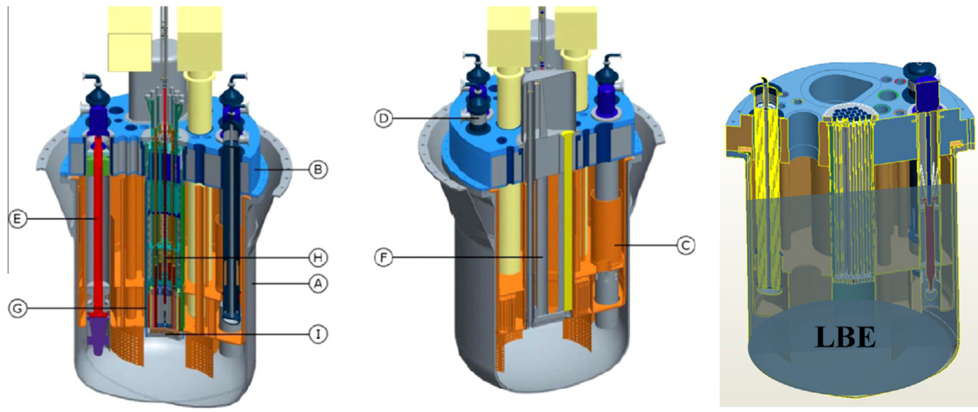

A. Reactor Vessel
B. Reactor Cover
C. Diaphragm
D. Primary Heat Exchanger
E. Primary Pump
F. In-vessel Fuel Handling Machine
G. Core
H. Above Core Structure
I. Core Restraint System

Fig. 1. MYRRHA nuclear reactor schematic and level of LBE coolant.

safety of nuclear reactors were given based on simple mechanical models (Thomas and et al., 1963), following the work of Housner (1957). The growing capabilities of CFD codes have made numerical simulation a popular tool for the study of sloshing problems and interface capturing methods can provide accurate prediction of the sloshing behavior inside the tank (Ibrahim, 2005; Faltinsen and Timokha, 2009; Mahaffy et al., 2007; Roelofs et al., 2013). For HLM reactors, different approaches to the problem have been proposed using Finite Element (Aquaro and Forasassi, 2005), Finite Volume (Gopala and Roelofs, 2009) and Smooth Particle Hydrodynamics (Vorobyev et al., 2011). The CFD code OpenFOAM has been used to simulate sloshing in the case of HLM reactor ELSY, providing qualitative and quantitative validation for the solver (Gopala and Roelofs, 2009). In the present study, further validation of this tool is attempted by comparison with dedicated experiments.

For the experimental investigation, the possibility to use water instead of liquid metals in a laboratory environment would simplify substantially the work. However, there is not a lot of information in the literature about how LBE or other liquid metals behave in sloshing situations. To demonstrate the effect of the liquid properties on the sloshing behavior, experiments using mercury and water are carried out on a laboratory set-up, presented in Section 2.1. Mercury is used in an attempt to approximate the properties of Lead Bismuth Eutectic (LBE) for the case of MYRRHA. The geometry of the reactor is simplified to a cylindrical shape to avoid other effects on sloshing and sinusoidal excitation signals are applied. The liquid elevation during sloshing experiments is measured using optical techniques. The same test-cases are reproduced numerically using a CFD code, discussed in Section 2.2. The results are presented in Section 3, showing comparisons between mercury and water and between experiments and CFD simulations. The study focuses on the resonance case, where the excitation frequency matches the first mode of the fluid in the tank, showing complex liquid motions. Conclusions regarding the validation of replacing liquid metal with water and the numerical modeling are drawn in Section 4.

2. Methods

Sloshing is studied experimentally on a laboratory scale model with simplified geometry using mercury and water. The same test cases are simulated numerically using the CFD code OpenFOAM.

2.1. Experimental study

Experimental investigation of the effect of the liquid properties on the sloshing behavior for the case of a cylindrical tank is carried out using optical methods. The excitation of the tank is imposed using the von Karman Institute shaking table facility named SHAKESPEARE (SHaking Apparatus for Kinetic Experiments of Sloshing Projects with EArthquake REproduction). This square shaped shaking table of 1.5 m size features 3-axis translations with three independent modules, one moving on each axis, as shown in Fig. 2. Hydraulic piston actuators are used to impose the motions of the table, controlled by a central computer through a feedback loop with position sensors. The maximum displacement is 45 mm on each axis, while the maximum acceleration is approximately 1.1 g, designed for loads up to 500 kg. The system can reproduce complex 3-axis earthquake time histories, which are loaded on the central controller, but any type of continuous signal within the aforementioned limitations can be prescribed.

The use of LBE in a laboratory environment poses several difficulties, as it has a melting point of 396.7 K and requires a heated tank to keep it liquid (Benamati and Sobolev, 2007). Using water for the sloshing experiments simplifies substantially the task, but verification is needed that it has similar behavior to liquid metals. For this purpose a comparison is made using water and mercury (Hg), which is liquid at room temperature and thus easier to use for sloshing. Special precautions have to be taken in the laboratory because mercury is toxic, so the tank has to be well sealed. The properties of LBE, water and mercury at their corresponding reference temperature are summarized in Table 1.

The use of mercury aims at comparing the sloshing behavior of a liquid metal to the one of water at similar conditions, in order to demonstrate the effect of different liquid properties (density, viscosity, surface tension). It is noted that in general the properties of the liquid have small impact on the natural frequency of sloshing, which is dominated by the size of the tank and the liquid height (Ibrahim, 2005; Abramson, 1966). Given that the sloshing effect is maximum at the case of resonance, it is very interesting to examine this case with the different liquids. Far from resonance, the liquid follows in general the excitation frequency of the tank, so it is expected that the effect on the liquid motion and the resulting forces will be smaller.

A problem that is often addressed in experimental studies of sloshing is the *scaling* of the model. As in most applications the