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Small scale experiments of sloshing considering the seismic safety of MYRRHA

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ABSTRACT

Sloshing can be a great concern for the seismic safety of heavy liquid metal cooled nuclear reactors, such as the Gen IV prototype MYRRHA, currently under development by the Belgian Nuclear Research Center (SCK•CEN). Sloshing is studied using reduced scale laboratory experiments on the SHAKESPEARE shaking table facility of the von Karman Institute. Scaling of the experimental model is discussed through dimensional analysis, identifying the appropriate scaling factors which are then applied to the seismic excitation signals. Qualitative results of the liquid sloshing motions inside the model are obtained with flow visualization, while moments are measured on an instrumented rod that is partially immersed in the liquid. A two component moment-balance is constructed to measure the bending moments on the element about the horizontal axes. The results demonstrate that sloshing, as a non-linear phenomenon, is highly dependent on the frequency of forcing relative to the natural frequency of the liquid in the specific container. In the resonance case the sloshing response reaches the highest amplitude and maximum moments are measured, representing a worst case scenario for the reactor safety. Experiments with internal components in the sloshing model indicate that obstructions reduce the sloshing loads and prevent resonance type sloshing. The proposed methodology with small scale experiments can provide a useful tool for the prediction of the sloshing effects for the MYRRHA design and safety analysis.

Abbreviations: ADS, Accelerator driven system; ATH, Acceleration time history; CFD, Computational fluid dynamics; DBE, Design basis earthquake; HDRB, High density rubber bearing (seismic isolators); HLM, Heavy liquid metal; IVFHM, In-vessel fuel handling machine; LBE, Lead–Bismuth-eutectic; MYRRHA, Multi-purpose hybrid research reactor for high-tech applications; SHAKESPEARE, Shaking Apparatus for kinetic experiments of sloshing projects with earthquake reproduction (shaking table).

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Nomenclature

A	displacement amplitude, m
a	acceleration, m/s^2
Bo	Bond number, -
Eu	Euler number, -
F	force, N
Fr	Froude number, -
f	frequency, Hz
g	gravitational acceleration, m/s^2
h	liquid height, m
k	gauge factor
L	length, m
l	length scale ratio, -
M	moment, Nm
R	electrical resistance, Ω
r	radius, m
Re	Reynolds number, -
t	time, [s]
U	velocity, m/s

Greek

ν	kinematic viscosity, m^2/s
ξ	natural mode parameter, -
ρ	density, kg/m^2
σ	surface tension, N/m
ω	angular frequency, rad/s

Subscripts

m	model
n	natural (1st mode)
p	prototype
R	ratio

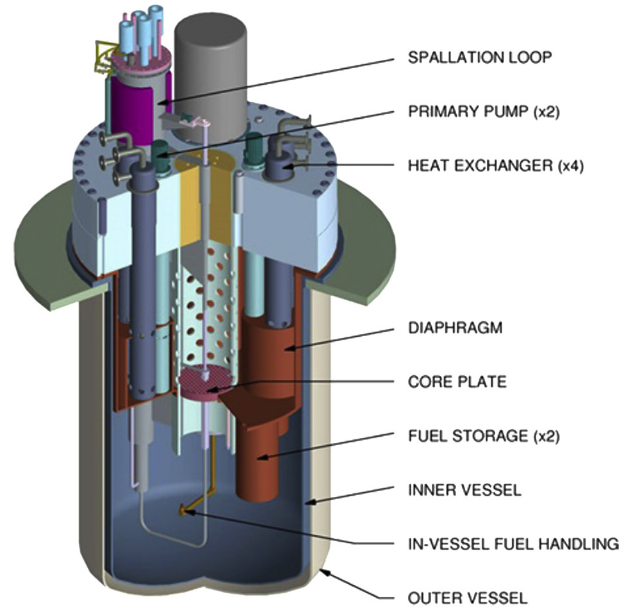

Fig. 1 – MYRRHA nuclear reactor schematic with main components.

Introduction

Seismic safety of nuclear reactors is brought to focus after the events of the Fukushima Daiichi nuclear disaster in March 2011. Concerns have been raised about safety and more measures are taken to prevent accidents in nuclear power plants worldwide [1]. In the case of innovative reactors (Gen IV), stricter requirements are being put in place by safety authorities to prove that the reactor is secure and minimize the risks of a serious accident in case of an earthquake.

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible experimental Accelerator-Driven System (ADS) under development at the SCK•CEN, the Belgian Nuclear Research Center, which uses Lead Bismuth Eutectic (LBE) for cooling [2]. A schematic representation of MYRRHA is shown in Fig. 1. Under seismic excitation, the heavy liquid metal in the partially filled nuclear reactor can be set to motion, known as *sloshing*, which can introduce extra loads on the structures and internal components [3]. These loads can be important taking into account the high density of liquid metal and are hard to predict because of the non-linear nature of sloshing. In this context, sloshing in MYRRHA is studied in order to investigate the effect of different parameters and to obtain a prediction of the forces and moments on the reactor structures.

Sloshing phenomena have been studied extensively and voluminous literature exists referring to different fields, ranging from aerospace and liquid transport to seismic safety of storage tanks and nuclear reactors [4,5]. Guidelines for the seismic safety of nuclear reactors have been given based on simple mechanical models [3], following the work of Housner [6]. However, the study of sloshing in complex geometries becomes difficult, as it is harder to obtain analytical expressions for the prediction of the natural modes and the liquid motion.

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 [4,5,7,8]. For HLM reactors, different approaches to the problem have been proposed using Finite Element [9–11], Finite Volume [12] and Smooth Particle Hydrodynamics [13].

Experimental study of sloshing in the context of nuclear reactor safety has been presented by Maschek et al. [14], to provide validation for CFD codes. Different aspects of sloshing experiments and scaling considerations for the laboratory model are addressed by Abramson et al. in the NASA report [15]. The possibility to use water instead of liquid metal is discussed by Myrillas et al. [16], along with the effect of liquid properties on the sloshing response.

In the present study reduced scale laboratory experiments are used to evaluate the sloshing response and resulting forces and moments. The scaling factors for the laboratory model are discussed and applied to the excitation signals. Cases with simple tank geometry and sinusoidal excitation are studied to measure the moments on an instrumented element immersed in the liquid. These can be also used as a basis for code validation for sloshing predictions. The sloshing motions in a complex geometry model for realistic earthquake