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Three-dimensional hydrodynamic modeling of the second shutdown system of an experimental nuclear reactor

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HIGHLIGHTS

- A CFD analysis was conducted for calculating the dynamics of the SSS of an experimental nuclear reactor.
- The numerical model solves coupled dimensionally heterogeneous systems using dynamic boundary conditions.
- The numerical model captures all the features of the physical phenomena.
- Details of 3D CFD simulation and validation procedure are outlined.
- The validated multiscale model points out that safety requirements are accomplished by the SSS of RA-10 project.

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ABSTRACT

A three-dimensional (3D) computational fluid dynamics (CFD) model is presented for the Second Shutdown System (SSS) of the experimental nuclear reactor RA-10 under design and construction by the Argentinian National Commission of Atomic Energy (CNEA). The RA-10 SSS consists on the drainage of the reflector tank surrounding the reactor core through a system of pipes in a limited amount of time solely by the action of gravity. The CFD model focuses on the 3D modeling of the reflector tank hydrodynamics and links the effects of the draining piping system through dynamics boundary conditions. The CFD model is first applied to a similar system, the RA-10 SSS Mockup, for which experimental data is available. Reasonable agreement is observed between the CFD model and the experimental observations for the RA-10 SSS Mockup. Finally, the validated CFD model is applied to the RA-10 SSS. The model results show that the performance of the RA-10 SSS meets the design requirements.

1. Introduction

The RA-10 is a new 30 MW_{th} multipurpose nuclear Research Reactor (RR) currently under design and construction by the Argentinian National Commission of Atomic Energy (CNEA) (Blaumann et al., 2013). The main objective of RA-10 will be the production of radioisotopes for medical purposes. This reactor will also provide irradiation testing facilities with neutron fluxes of the order of $10^{14}\,\frac{n}{cm^2}$ to support CNEA programs on material sciences and on nuclear fuels design. The reactor irradiation facilities are located in the heavy water reflector tank surrounding the reactor core (see Fig. 1a).

The heavy water in the reflector tank plays a central role in diminishing the neutron losses by increasing neutron re-entrance to the reactor core. The drainage of the reflector tank provides a redundant and independent safety system by allowing neutron losses from the reactor core. This is called the reactor Second Shutdown System (SSS). The reactor First Shutdown System (FSS) is based on the insertion of control rods.

Safety requirements to the RA-10 SSS demand the reflector tank to be drained to half its volume in a limited amount of time (55% of its height after 15 s) solely by the action of gravity. A three-dimensional (3D) computational fluid dynamic (CFD) model of

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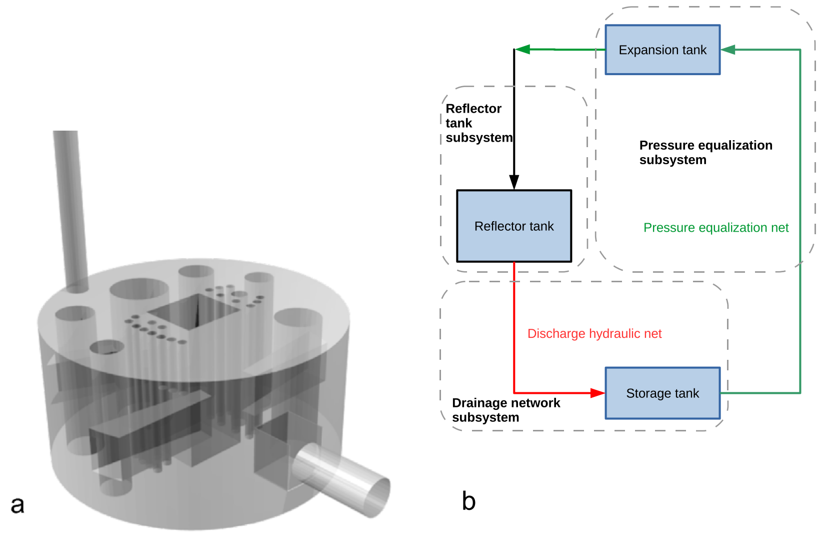

Fig. 1. (a) Reflector tank of RA-10 SSS. (b) Diagram of the RA-10 SSS decomposed into three subsystems. (Black) Reflector tank subsystem. (Red) Drainage network subsystem. (Green) Pressure equalization line subsystem. The arrows indicates the direction of the flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the RA-10 SSS has been performed in order to confirm that safety requirements are met. The RA-10 SSS is composed by three different subsystems (see Fig. 1b): the reflector tank, the drainage network subsystem and the pressure equalization subsystem.

The reflector tank drainage involves complicated 3D free surface hydrodynamics, which has to be modeled in detail. On the other hand, the flow through the drainage and pressure equalization subsystems can be simplified and described by zero-dimensional models. This decomposition and conceptualization strategy was proved to be effective in similar problems (Leiva et al., 2010; Leiva et al., 2011). The challenge in this modeling approach is to solve the coupled system (Buscaglia et al., 2005).

The hydrodynamic modeling of the RA-10 SSS implemented in this work focuses on the 3D CFD modeling of the reflector tank. The interaction between the reflector tank subsystem and the drainage and pressure equalization subsystems is made possible by implementing dynamic boundary conditions in the 3D CFD modeling using a weak-coupling technique. The 3D CFD model is first applied to the RA-10 SSS Mockup for which experimental data is available. The validated model is then employed to make predictions on the performance of the RA-10 SSS.

This work is organized as follows. Section (2) describes the main features of the RA-10 SSS. Section (3) presents the 3D CFD model of the reflector tank together with the strategy for connecting the different subsystems by dynamics boundary conditions. Section (4) presents validation results by comparing experimental observations to the 3D CFD model results of the RA-10 SSS Mockup. Section (5) presents the results of the 3D CFD model applied to the RA-10 SSS. Finally in Section (6), the conclusions are summarized.

2. General description of the RA-10 SSS.

The RA-10 SSS is mainly composed by three subsystems: the reflector tank, the discharge hydraulic net and the pressure equalization line. A simple diagram is shown in Fig. 1b. When the SSS is required to act, a manifold of six valves located in the discharge hydraulic net opens and the heavy water starts to drain solely by the action of gravity. The heavy water flows from the reflector tank through the discharge net to a storage tank located below the reactor core level. The pressure at the storage tank and over the top of the reflector tank are equalized by a pressure equalization line.

Table 1
Main characteristics of both cases: RA-10 SSS Mockup facility and RA-10 SSS.

Characteristic	Mockup	RA-10
Tank height [m]	1.215	1.000
Tank radius [m]	1.300	1.000
Diameter of upper connection [m]	0.1524	0.1524
Diameter of discharge pipe [m]	0.2540	0.2647
Net volume [m^3]	5.558	2.492
Volume of internals [m^3]	1.041	0.649
Working fluid	Light water	Heavy water
Working cover gas	Air	He
Working pressure cover gas [Pa]	92000	121300

A cover gas fills up the storage tank, the pressure equalization line and part of the expansion tank. During the performance of the SSS, the cover gas enters the reflector tank through a connection located in the upper part which is partially filled with heavy water under normal operation conditions. The system cover gas is helium.

The overall hydrodynamics of reflector tank is mainly controlled by the discharge hydraulic net and the pressure equalization line. The discharge hydraulic net imposes a pressure condition on the outflow of the reflector tank. In the same way, the equalization pressure line imposes a pressure condition on the cover gas. Incorporating the complete coupled system in the modeling for the hydrodynamics of the RA-10 SSS is mandatory.

An experimental facility has been built and operated in the past to address the hydrodynamics of a similar system to the RA-10 SSS (Villarino and Doval, 2011). In the context of the present work this facility is called RA-10 SSS Mockup. The RA-10 SSS Mockup geometry is similar but larger than the RA-10 SSS. Main features for both cases are listed in Table 1. The experimental observations of the RA-10 SSS Mockup are used to validate the 3D CFD model.

3. Three-dimensional computational fluid dynamic model for the reflector tank

The reflector tank geometry is shown in Fig. 1a. All the irradiation facilities are housed inside the reflector tank, which generate a complicated geometry of the system to model. On the other hand, as the reflector tank drains, helium fills the system generating a