Computers and Mathematics with Applications 67 (2014) 2228–2239

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

A fast algorithm for 3D simulation of thermal stratification in containment pools of nuclear power plants

T. Gornak [a], O. Iliev [a,c,d], P. Minev [b,*], A. Zemitis [a]

[a] Department of Flows and Materials Simulation Fraunhofer Institute for Industrial Mathematics, Fraunhofer-Platz 1, Kaiserslautern, Germany

[b] Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2G1

[c] King Abdullah University of Science and Technology, KAUST, Saudi Arabia

[d] Technical University of Kaiserslautern, Kaiserslautern, Germany

ARTICLE INFO

Article history:
Available online 13 April 2014

Keywords:
Nuclear reactor safety simulations
Boussinesq equations
Splitting methods

ABSTRACT

Safety analysis is of ultimate importance for the operation of Nuclear Power Plants (NPP). Experiments even on a pilot scale are quite expensive and therefore numerical simulations play a major role in this analysis. They allow to predict the behaviour of NPP systems under different operational and accident conditions and to develop proper action plans for minimizing the risks of accidents, and minimizing the consequences of possible accidents. For a proper risk assessment and development of emergency plans, a very large number of scenarios have to be simulated, achieving acceptable accuracy for the critical parameters, such as radioactive pollution and temperature. The existing software tools are either very simplistic and therefore quite inaccurate or they use general CFD codes that makes them very slow. This paper presents a customized algorithm and corresponding software tools for simulation of non-isothermal flows in the containment pool of a NPP. It first summarizes the requirements for such simulation tools and then presents the new algorithm which, in the opinion of the authors, is a proper compromise between accuracy and efficiency for solving such problems. It uses a Fictitious Domain Method (FDM) to impose the boundary conditions, a Cartesian finite volume discretization combined with a Domain Decomposition (DD) technique, and a factorized perturbation of the incompressibility constraint proposed recently in Guermond and Minev (2010). Finally, results from numerical simulations in idealized and realistic geometries are presented and discussed.

1. Introduction

Safety analysis is of ultimate importance for the proper operation of Nuclear Power Plants (NPP). In most cases it is impossible or undesirable to perform experiments simulating accidents in NPP. Therefore, numerical simulations are the only feasible tool that can be used to test a large number of possible accident scenarios and devise a proper containment strategy for each one of them. In the present paper we consider the so-called "lost of coolant accident" that may occur in the containment building. A containment building typically is a several-story building of a complicated shape, and it is designed as a passive safety system for some types of nuclear reactors, e.g. pressurized water reactors (PWR) and boiling water reactors (BWR). Its main purpose is the prevention of leakage of radioactive water in case of accidents. Presently, the

* Corresponding author. Tel.: +1 780 492 3398.
E-mail addresses: gornak@itwm.fhg.de (T. Gornak), iliev@itwm.fhg.de (O. Iliev), minev@ualberta.ca (P. Minev), zemitis@itwm.fhg.de (A. Zemitis).

http://dx.doi.org/10.1016/j.camwa.2014.03.011
0898-1221/

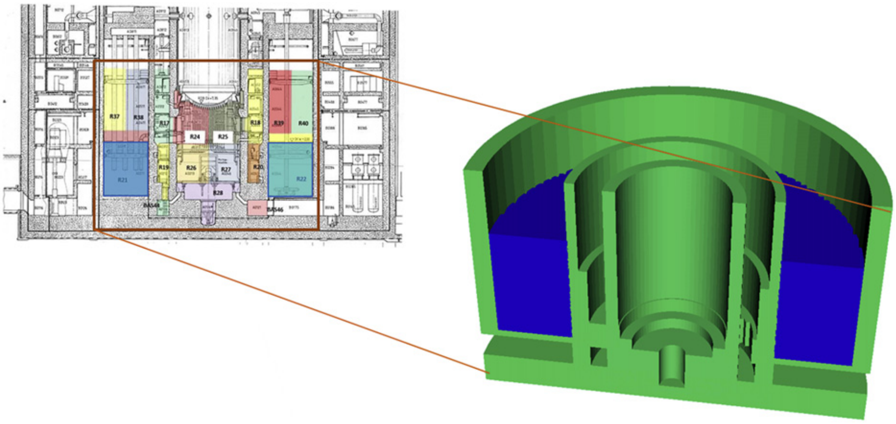

Fig. 1. One part of computational domain and cross section of the real domain.

most widely used tools for computation of the pressure head and average temperature are based on the so-called Lumped Parameter (LP) codes (also called ''codes for space averaged quantities''), such as COCOSYS [1]. Their main advantage is that they are very fast while they still include a well-validated description of the chemical and physical processes occurring in the containment building. On the other hand, the LP models are too simplistic to resolve the spatial stratification of the flow that might be critical in the lower part of the containment building, the so-called containment pool, where the radioactive water is collected. Recently, some 3D CFD codes have been employed for that purpose and they naturally allow for very detailed and accurate simulations. However, in a large part of the containment building, particularly at the higher floors occupied by air, the LP models are accurate enough and there is no need for very detailed simulations. Furthermore, full 3D simulations require much pre-processing time and large computational resources. As a result, it would be impossible (or better to say extremely expensive) to run a large number of accident scenarios in a 3D setting. The present study is aimed at the development of an algorithm and software that compromises between these accuracy and efficiency requirements and is specifically designed to perform simulations of stratified flows in the containment pool on relatively simple computer systems. Before we proceed with the description of the algorithm, we briefly discuss the most essential features of the heat and fluid flow in the containment pool and the requirements to the numerical simulation tools.

• The geometry of the containment pool is usually quite complicated, (see Fig. 1 for a typical example). Nevertheless, the flow domain can be well approximated using binary compositions of objects of a simple shape. This allows for the development of a fast and easy to use pre-processor described in [2] (see also Section 2 of the present paper).

• The flow in the containment pool is a free surface flow. However, the free surface effects are important only at the initial stage of its flooding. At later stages, since the depth of the water in the pool becomes significant, it is reasonable to assume that the free surface is flat and the pressure on it is constant. Such an assumption, however, prevents us from a complete description of the flooding process since it does not provide a mechanism for flooding the neighbouring rooms after a given room is full of water. The present approach involves a carefully managed system of localized sources and sinks that allow for the simulation of such scenarios.

• During an accident, the temperature of the water entering the containment pool is significantly different than the water in the pool and this leads to thermal mixing and stratification. As a result, the average temperature in the pool can differ significantly from the temperature at the air–water interface. The LP approach ignores this difference and uses the average temperature in the pool to compute the rate of various reactions occurring in the air or at the air–water interface that can result in very inaccurate predictions. This is one the main reasons for the development of the present customized algorithm and the software tool CoPool, [3].

• The containment building is surrounded by a very thick concrete wall. The relatively low thermal conductivity of the concrete and the large difference between the inside and outside temperature result in the development of a thermal boundary layer inside the containment wall. Its effect cannot be properly resolved by the LP approach and therefore in the present customized approach we employed a specialized overlapping Domain Decomposition (DD) technique to resolve the thermal problem inside the containment wall. It is briefly discussed in Section 5.

• In general, the accuracy requirement to the local values of the water velocity and pressure are not high, as long as the thermal stratification is properly accounted for, and the pressure drop is accurately evaluated. The accuracy of the pressure drop computation is crucial for the proper design and operation of the pumps positioned at the bottom of the containment pool.

Based on these observations and requirements, we developed a customized algorithm and a computer code that are aimed at achieving a reasonable compromise between accuracy and efficiency in the simulations of a large number of emergency scenarios for the containment pool of NPPs. It employs a finite volume discretization on Cartesian grids for the heat and fluid flow and a fictitious domain approach for imposition of its boundary internal boundary conditions. The pressure is computed also by a fictitious domain approach using a factorized perturbation of the incompressibility constraint