Progress in Nuclear Energy 78 (2015) 101–109

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Analysis of hydrogen flame acceleration in APR1400 containment by coupling hydrogen distribution and combustion analysis codes

Jongtae Kim*, Seong-Wan Hong

Korea Atomic Energy Research Institute, Severe Accident and PHWR Safety Research Division, South Korea

A R T I C L E I N F O

Article history:
Received 17 July 2014
Received in revised form
4 September 2014
Accepted 11 September 2014
Available online 29 September 2014

Keywords:
Hydrogen distribution
Hydrogen combustion
Flame acceleration
Containment
Severe accident
Station blackout

A B S T R A C T

This study was conducted as part of the construction of an integrated system to mechanistically evaluate flame acceleration characteristics in a containment of a nuclear power plant during a severe accident. In the integrated analysis system, multi-dimensional hydrogen distribution and combustion analysis codes are used to consider three-dimensional effects of the hydrogen behaviors. GASFLOW is used for the analysis of a hydrogen distribution in the containment. For the analysis of a hydrogen combustion in the containment, an open-source CFD (computational fluid dynamics) code OpenFOAM is chosen. Data of the hydrogen and steam distributions obtained from a GASFLOW analysis are transferred to the OpenFOAM combustion solver by a conversion and interpolation process between the solvers. The combustion solver imports the transferred data and initializes the containment atmosphere as an initial condition of a hydrogen combustion analysis. The turbulent combustion model used in this study was validated by evaluating the F22 test of the FLAME experiment. The coupled analysis method was applied for the analysis of a hydrogen combustion during a station blackout accident in an APR1400. In addition, the characteristics of the flame acceleration depending on a hydrogen release location are comparatively evaluated.

1. Introduction

During a core melt accident in a nuclear power plant (NPP), a large amount of hydrogen can be generated in a nuclear reactor and released into the reactor containment (OECD/NEA, 1999). Hydrogen combustion can occur in the containment when the concentration is higher than a flammability limit (OECD/NEA, 1999). During the propagation of the hydrogen flame, the flame front is distorted and stretched by obstacles existing in the flow path, and is accelerated by interaction with the generated turbulence (Dorofeev et al., 1999). The most severe case by the hydrogen combustion is the occurrence of a detonation, which induces a few-fold greater pressure load (OECD/NEA, 2000) on the containment wall than a deflagration flame. The occurrence of a containment-wise global detonation is prohibited by a national regulation (OECD/NEA, 2014). However, there is a possibility of compartment-wise local detonation.

At the time of a hydrogen release, a gas mixture cloud containing highly concentrated hydrogen flows from a release location by a jet momentum and moves upward by buoyancy force. The compartments located in the flow path such as a steam generator (SG) compartment, an annular compartment, and a dome region are likely to have highly concentrated hydrogen. In a mixing period, which is a time after the hydrogen release period, the behavior of the hydrogen mixture cloud becomes very complicated by a release of steam following the hydrogen release, volumetric and wall condensation of steam, hydrogen recombination by passive autocatalytic recombiner (PAR), and spray activation. Thus, it is important to accurately predict the possibility of hydrogen accumulation during the hydrogen release and mixing periods. If it is found that hydrogen concentration in any compartment is far below a detonation criterion during an accident progression, it can be thought that the occurrence of a detonative explosion in the compartment is excluded. However, if it is not, it is necessary to evaluate the characteristics of flame acceleration in the containment.

The possibility of a flame transition from a deflagration to a detonation (DDT) can be evaluated from a calculated hydrogen distribution in a compartment using sigma-lambda criteria (Breitung and Dorofeev, 1999). However, this method gives a result

* Corresponding author. Severe Accident and PHWR Safety research division, Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon 305-353, South Korea. Tel.: +82 42 868 8261; fax: +82 42 866 6155.
E-mail addresses: ex-kjt@kaeri.re.kr, mr.kimjt@gmail.com (J. Kim).

http://dx.doi.org/10.1016/j.pnucene.2014.09.003
0149-1970/

with an uncertainty because the geometric characteristics of a real compartment are not considered well. Some experimental studies have been conducted to evaluate geometric effects on the hydrogen flame propagation. In the FLAME (Sherman et al., 1989) experiment conducted by Sandia National Lab. (SNL), the characteristics of hydrogen flame acceleration in a channel affected by obstacles and opening of the upper wall was tested. In the ENACCEF (Bentaib et al., 2007) experiment, it was observed that an accelerated hydrogen flame by baffles in the pipe of the test is decelerated before entering the consecutive dome region. In parallel to the experimental works, some efforts were devoted to develop a three-dimensional analysis method of hydrogen flame acceleration in an NPP containment. The TONUS code has been developed by IRSN and CEA for an evaluation of a hydrogen safety in an NPP containment by mechanistically simulating a hydrogen combustion (Kudriakov et al., 2008). Kotchourko et al. (1999) developed COM3D and applied it to evaluate the hydrogen flame acceleration in an NPP containment.

To evaluate the containment integrity from a threat of a hydrogen explosion, it is necessary to establish an integrated evaluation system, which contains a hydrogen generation, distribution and combustion analysis methods. In addition, it may include a method for a containment structure analysis with a pressure load caused by a hydrogen combustion.

The purpose of this study is to develop a multi-dimensional analysis method for a mechanistic evaluation of hydrogen flame acceleration characteristics in an NPP containment by coupling the hydrogen distribution and combustion analysis codes. The GASFLOW code (Travis et al., 2011), which was initially developed by LANL and has been continuously upgraded by KIT, is selected for the analysis of a hydrogen distribution in the containment because it is well-validated and it is applicable for a simulation of a long-term accident progression by its fast running capability. For the analysis of a hydrogen combustion in the containment, an open-source CFD (computational fluid dynamics) code OpenFOAM (Weller et al., 2014) is chosen. OpenFOAM is composed of application programs for field simulations and libraries of the models implemented in the applications. The reason for choosing OpenFOAM is an easy development of interface tools by using the libraries.

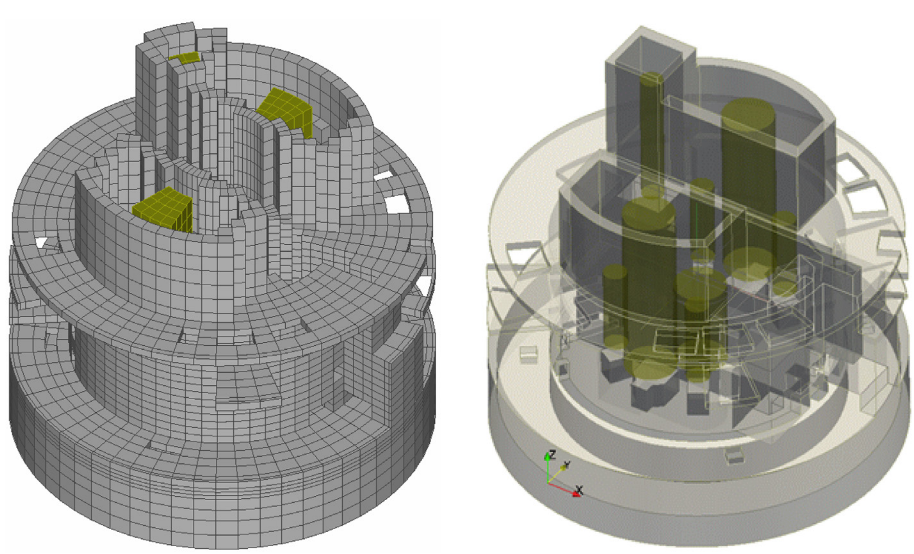
In the coupled analysis system, data on the hydrogen distribution obtained from a GASFLOW analysis is transferred to the OpenFOAM combustion solver using a data conversion program developed in this study. The combustion solver imports the transferred data and initializes the containment atmosphere as an initial condition of a hydrogen combustion analysis. A validation of the GASFLOW code for a hydrogen distribution analysis is omitted in this study because many efforts have already contributed to the validations (Schwarz et al., 2011; Royl et al., 2009). In this study, a turbulent combustion model applied for the analysis of hydrogen flame acceleration is validated by evaluating F22 test of the FLAME experiment. The coupled analysis method is applied for the assessment of the possibility of a hydrogen flame acceleration during a station blackout (SBO) accident in an APR1400 (KHNP, 2014). The characteristics of the flame acceleration depending on a hydrogen release location were comparatively evaluated.

2. Coupled method for analysis of hydrogen flame acceleration

Here, a method for coupling the multi-dimensional hydrogen distribution and combustion analysis codes to mechanistically evaluate the flame acceleration characteristics with a geometric effect is described.

2.1. Containment modeling

GASFLOW is used in this study for the analysis of a hydrogen distribution in an NPP containment. It is a finite-volume CFD code that solves unsteady compressible Navier–Stokes equations with gas species transport in a three-dimensional domain. In order for a fast simulation of a long-term accident progression in the containment, it uses orthogonal meshes on a Cartesian or cylindrical coordinate system. For this reason, it requires a great amount of man-power to manually identify mesh cells belonging to the internal structures of the containment. It is impractical to exactly model the general shapes of the structures with Cartesian or cylindrical coordinates. The surfaces of the structures must be approximated to conserve a free volume in the containment. For a GASFLOW analysis of the APR1400 containment, a cylindrical coordinate system is selected to reduce dead cells and stair-shaped walls. Fig. 1 (a) shows the computational cells of the solid structures in the containment.



(a) (b)

Fig. 1. Geometric model of APR1400 for (a) GASFLOW and (b) OpenFOAM analyses.