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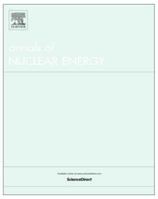

Numerical study on the influence of steam condensation on hydrogen distribution in local compartments

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ABSTRACT

In the course of a severe accident in a PWR nuclear power plant, gas mixture is released into one compartment and transfers into other compartments through narrow channels. Heat and mass transfer induced by condensation and convection play a key role in hydrogen distribution process. To evaluate the performance of different models on account of analogy theory in steam condensation on the wall with non-condensation gas in local compartments of PWR plant, a 3D model consisting of four vessels designed to cover typical geometry and gas flow characteristic of real compartment is built and analyzed with 3D CFD code. Three models are selected for comparison, i.e. Reynolds analogy, Von Karman analogy, similar velocity-temperature (v-t) profiles analogy. Furthermore, resultant influence on hydrogen distribution in horizontal and vertical connected compartment is also discussed. The results show that hydrogen distribution and steam condensation on the wall of compartment simulated by Von Karman analogy model and Reynolds analogy model are consistent with each other. While the similar v-t profiles model over-predicts the condensation rate on the wall in the whole system. Stronger wall cooling leads to less hydrogen transferring into non-source compartments leading to underestimation of hydrogen risk here for both vertically and horizontally connected compartments.

1. Introduction

In the course of a severe accident in a PWR nuclear power plant, large amounts of hydrogen could be generated from zirconium-water reaction due to lack of coolant in the reactor core. Hydrogen with steam produced by the evaporation of the coolant is released into containment through the break of first circuit, then flows and mixes in several local compartments. Usually, hydrogen distribution in containment is not uniform under multi-factor effects such as gas diffusion, jet momentum, buoyancy, geometrical structure and so on, resultant flammable mixture of gases are likely to deflagration or detonation, which threaten the system equipment and integrity of containment. Comparing with large upper space of containment, high concentration of hydrogen and resultant hydrogen risk is more possible to form in limited space where gas mixture is released transferred into other compartments through narrow channels. Besides, according to the general technology requirements put forward by National nuclear safety administration (NNSA) after the Fukushima accident, combustion and explosion due to locally hydrogen accumulation is pointed out particularly as a major threat to containment integrity (NNSA, 2012). Therefore, hydrogen flow and distribution behavior in local compartments needs sufficient attention.

CFD method has been widely applied to reflect geometrical structural features in local compartments precisely. For the analysis at full-scale containment scale, Baraldi et al. (2007) perform numerical simulation about the effect of break size and location on hydrogen distribution among different compartments of European Pressure Reactor (EPR) during depressurization process combining CFX and REACFLOW. Kim et al. (2005) analyze hydrogen flow in local compartments of APR1400 under the influence of ventilation gap of in-containment refueling water storage tank (IRWST) with GASFLOW code. Li et al. (2018) simulates gas natural convection in limited square cavity and containment. More recent development could be found in Refs (Xiao et al., 2017; Zhang et al., 2017). For small local compartment scale, Liu and Cao (Liu et al., 2017) present numerical study on hydrogen flow behavior in two compartments with different connecting pipes. Above research mainly focus on the effect of geometric structure on hydrogen flow characteristic.

Heat and mass transfer induced by steam condensation and convection play a key role in hydrogen distribution process because of large amount of steam injecting with hydrogen into local compartments in severe accident condition. Besides, the

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presence of non-condensable gas has a great influence on the heat transfer resistance in the liquid-vapor interface. The non-condensable gases are carried with the vapor towards the interface where they accumulate (Martin-Valdepenas et al., 2005). Firstly, the presence of non-condensable gas reduces steam partial pressure so the saturation temperature decreases as well, which reduces the temperature difference, i.e. driven force of condensation between gas and wall. Secondly, before contacting solid wall, steam should transport through non-condensable gas layer by diffusion, which is resistance of steam transportation. Many heat and mass transfer models are developed in the last several decades, which can be divided into boundary layers and full three-dimensional equations model, modeling based on heat and mass transfer analogy theory, diffusion layer model and experiment-based correlations (Yadava et al., 2016). In CFD analysis, model based on analogy theory is commonly adopted since it can reflect the heat transfer mechanism and require relatively less computing resources.

Steam condensation on the wall will decrease the steam mole fraction in the source term compartment, meanwhile creates downwards flow near the condensing wall leading to natural convection inside the source term compartment. On one hand, the lower steam concentration will lead to high concentration of hydrogen resulting in higher hydrogen source for other compartments. On the other hand, the natural convection will influent the flow behavior near the connected pipe in the source term compartment, consequently influent the hydrogen transferring into other compartments. Former research shows that the gas transfer between compartments is overpredicted in integral computer codes such as MAAP (Lee et al., 2017), GOTHIC (Holzbauer and Wolf, 2017) because of the neglection of the near wall flow behavior. Therefore, it is necessary to conduct this study on the influence of steam condensation on the gas transfer in local compartments.

The object of this study is to evaluate the performance of different heat transfer model on account of analogy theory in steam condensation on the wall in local compartments, and also to further discuss the effect of steam condensation on hydrogen transportation from one to another compartment. In this paper, two connecting types between compartments are modeled with simplified compartments screening from the Design Control Documents (AP1000 Design Control Document, 2011) and Probabilistic Risks Assessment of AP1000, i.e. vertical connecting compartments and horizontal connecting compartments. 3D models of these two systems that designed to cover typical geometry and gas flow characteristic of real compartment are built and analyzed with 3D CFD computer code. Three heat transfer models are selected for comparison, i.e. Reynolds analogy, Von Karman analogy, similar velocity-temperature (v-t) profiles analogy. Furthermore, hydrogen distribution using different heat transfer model in compartments is also discussed.

2. Modeling of compartments

2.1. Vessel design and geometrical modeling

The main objective of this study is to capture the major phenomena related to containment thermal hydraulics with rather simplified geometry. Firstly, refer to the results and insights of probabilistic risk assessment (PRA) in AP1000 Design Control Document (AP1000 Design Control Document, 2011), the main paths of hydrogen release and flow in the containment during accidents are from passive core cooling system (PXS) compartment and chemical and volume control system (CVS) compartment to core makeup tank (CMT) compartment, reactor coolant system (RCS) piping rupture and the vent of in-containment refueling water storage tank (IRWST). Previous study also shows that hydrogen is more likely to flow through or gathered in these compartments (Wang and Cao, 2017). In general, the direction of connecting pipes can be divided into horizontal and vertical, hence these two typical connection types are adopted in vessel design.

Secondly, based on the phenomena identification and ranking (PIRT) result for containment thermal hydraulics and hydrogen distributions in the state-of-the-art report (SOAR) by OECD/NEA (1999), we count all important phenomena i.e. rank is high (H) with quality factor is gas composition, as shown in Table 1. From the table, it can be summarized that buoyancy/stratification and free convection should be reflected in designed vessel. Similar PIRT results also present in the report of containment code validation matrix published by OECD/NEA (2014), in this report, we further summarize relevant facilities which can simulate above important phenomena. As shown in the last column of Table 1. The facilities with local compartment geometric feature are further filtered out of the facilities in Table 1, i. e. PANDA, THAI and TOSQAN.

A design scheme of which the vessel No.1 and No.2 connected with a horizontal pipe and the vessel No.3 and No.4 connected with a vertical pipe is developed, as shown in Fig. 1.

Fig. 1(a) and (b) shows two 3-dimensional CFD geometrical models of compartments (four vessels) built in Cartesian coordinates and mesh division. The volume of No. 1 and No. 2 vessel is 12 m^3, No. 3 and No. 4 vessel have the volume of 6 m^3 and 11.5 m^3. In the first model, hydrogen injection nozzle is located at the bottom of left No.1 vessel. In the second model, hydrogen is injected near the right side from the bottom of lower No.4 vessel. The computational domain is discretized by structured grid. Based on the grid sensitivity analysis, three mesh schemes are set, they are coarse (about 20,000 cells), medium (about 90,000 cells), fine (about 150,000 cells), as shown in Fig. 2, as for simulation result of hydrogen concentration near the inlet nozzle, there is deviation between coarse scheme and other two schemes. For accuracy and computation cost, the medium mesh scheme is finally adopted. Besides, mesh division where relatively high gradient of hydrogen concentration appears (near the nozzle) and near complex solid structures (connecting pipes) is refined. The y+ of compartment model is about 35.

2.2. Initial and boundary conditions

In the investigated scenario, air is filled in compartments at the beginning of simulation ($t = 0$ s). The gas mixture of hydrogen and steam is injected into source compartment from a nozzle located in the bottom, the total mass flow rate is 3.1 g/s and hydrogen mass flow rate is 0.1 g/s. The diameter of inlet nozzle is 3 cm, initial velocity is 9.3 m/s and inlet Reynolds number is 1.07×10^4. It is assumed that two kinds of gas have been mixed uniformly. No-slip boundary condition is adopted on all of solid wall. On the inner face of wall, heat and mass transfer between gas and solid structure are considered. The initial temperature of wall is 298.15 K. Boundary condition on external surface is assumed to be cooled by natural air convection. The wall thickness is 2.5 cm. A constant temperature (298.15 K) and heat transfer coefficient (10 W/m^2K) are set. The initial pressure and temperature of atmosphere in vessel are 0.1 MPa and 298.15 K.

2.3. Physical model

As for mass, momentum and energy transport property, the mass diffusion coefficient, kinematic viscosity and thermal conductivity of gas mixture are calculated by the relationship of Curtiss and Hirschfelder (Curtiss and Hirschfelder, 1949), the semi-empirical formulas of Wilke (1950), the relationship of