

Three Dimensional Gas Mixing inside In-containment Refueling Water Storage Tank (IRWST) of the KNGR

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Abstract

Three-dimensional gas mixing behavior inside in-containment refueling storage tank (IRWST) of the Korean next generation reactor (KNGR) is analyzed using the computational fluid dynamic (CFD) code, FLUENT, to demonstrate applicability of lumped parameter model to hydrogen mitigation system engineering design. Flow and geometrical boundary conditions are considered conservatively and the standard k- ϵ model is used for the turbulence simulation. Calculations for average hydrogen and steam release conditions for the typical KNGR accident sequences show that gas mixing time inside the IRWST is about hundred seconds, very short compared with hydrogen release duration of thousands of seconds. It is concluded that the lumped parameter model is practically applicable to the IRWST region with respect to gas mixing.

1. Introduction

For the licensing of an advanced pressurized water reactor, it should be demonstrated that hydrogen concentration in the containment is maintained below detonable level under core melting severe accident conditions [1]. In this regard, computer codes based on lumped parameter models (LPM) have been widely used for engineering purpose even though they cannot simulate realistic multi-dimensional flow behavior.

In order to apply the LPM to practical engineering problems, a number of experimental correlations are necessary to compensate for lost physics due to large (lumped)

computational cells. Of course, the LPM codes should be validated against experimental data and/or field codes which can treat computational domain into much finer computational cells. In this regard, worldwide efforts have been imposed to validate LPM codes and the result is that they are reasonably practicable to relatively fast mixing environment where average value obtained from a lumped volume appropriately represents the physics inside.

For the hydrogen mitigation system design in the KNGR (a large evolutionary pressurized water reactor with 4,000 MWt), a licensing question has been raised on the applicability of LPM to a particular regions inside the compartments such as in-containment refueling storage tank (IRWST), steam generator rooms, and reactor cavity.

Among them, IRWST is of primary interest since it directly receives gaseous effluents from reactor coolant system (RCS) relief valves under high-pressure core melting accidents and it has a shallow and donut-like free board space above water level as shown in Fig. 1 [3] in which gas mixing appears inefficient. In engineering calculation using MAAP4 [2] for the KNGR hydrogen mitigation system design, IRWST is treated as one control volume.

The objective of this paper is to demonstrate applicability of LPM for the KNGR IRWST by analyzing three-dimensional mixing behavior of gases for typical accident sequences using commercial computational fluid dynamic (CFD) code, FLUENT [4]. The main focus is on pure gas mixing rather than chemical reactions due to operation of hydrogen mitigation system (HMS) such as catalytic recombiners and igniters.

2. Analysis of Gas Mixing inside IRWST

The IRWST of the KNGR is schematically shown in Fig. 1. The primary purpose of the IRWST is refueling. However, under accident conditions, the IRWST plays as a mass and energy sink, which takes in high energy RCS effluents. The inner and outer radii are 53 ft (16.15 m) and 71 ft (21.90 m), the height of the freeboard space in the IRWST above the normal water level is 4 ft. There are sparger pipes connected to pressurizer safety-relief valves (Pilot Operated Safety Relief Valves, POSRVs) and they are for mitigating hydrodynamic load from the RCS effluents by dispersing the flow. For the purpose of gas venting under high-pressure, there are four pressure relief dampers above the IRWST.

Each damper has an area of 36 ft² (3.24 m²) and operates passively under differential pressure of 20 psi.

The given mixing problem inside the IRWST shown in Fig.1 can be treated in a conservative manner by using assumptions which make temporary hydrogen concentration differential greater than practical situation. IRWST freeboard gas space is geometrically modeled as following (see Fig. 2):

- For the volume, a value for normal operating condition is used even though we will have larger volume when the IRWST water can be used for reactor cavity flooding.
- Distributed spargers, from which gases are dispersed, are modeled as one inlet flow area of 5.75m x 6 m
- Four dampers are modeled as one outlet vent which has an area of 2m x 2m (4 m²) and always opened (exact modeling of damper is unnecessary for this kind of mixing problem),
- The outlet vent is located at the opposite side of the inlet flow, and
- There is no hydrogen mitigation system which surely promotes global mixing

The type and number of the computational mesh cells for the fluid domain is hexagonal and 11,072, respectively by assuming symmetry at the central plane of inlet and outlet vent. Also, assumptions for physical properties, initial and boundary conditions and calculation models are:

- Fluids (gases) in the IRWST freeboard space is incompressible and ideal gases,
- IRWST water surface is a standard wall boundary condition with small roughness constant of 0.01,
- The wall temperature is initially 300K, and the water surface temperature is initially 400 K.
- The fluid domain is initially occupied with 100% mole fraction of steam (H₂O) and the initial temperature distribution is calculated with above boundary conditions.
- Mixture of two gas species, hydrogen and steam with given temperature and velocity is injected through the inlet area with fixed mass fractions,
- Gravity effect is not considered since the height of the IRWST freeboard space is shallow compared with its length, and
- The inlet turbulence values for k and ϵ are assumed uniform and calculated as recommended in the FLUENT as following [3]:

The turbulent kinetic energy k is given by

$$k = \frac{3}{2}(u_{avg}I)^2 \quad (1)$$

where u_{avg} is the magnitude of the mean velocity specified and I is the turbulent intensity. The turbulent intensity, I , can be obtained by using following equations for pipe flow:

$$I \sim 0.16(\text{Re}_{D_H})^{-1/8} \quad (2)$$

The turbulent dissipation rate can be obtained by

$$\mathbf{e} = C_m^{3/4} \frac{k^{3/2}}{l} \quad (3)$$

where C_m is an empirical constant approximately 0.9 and l is turbulence length scale. l for fully-developed duct flow is

$$l = 0.07D_H \quad (4)$$

where D_H is the hydraulic diameter for a fully developed flow. A factor 0.07 in Eq.(4) is based on the maximum value of the mixing length in a fully-developed turbulent pipe flow. For the inlet flow area 5.75 m x 6 m rectangle assumed in this paper, $D_H = 5.87$ m.

Inlet gas thermo-physical condition depends on the accident sequence. The accident sequences selected for the KNGR are LOFW-17 and SBO-22 which are dominant accidents [3]. LOFW-17 is a total loss of feedwater accompanying RCS depressurization by opening pressurizer POSRVs before core damage. SBO-22 is a station blackout sequence without recovery of electric power for ten hours with turbine driven auxiliary feedwater pumps working only for eight hours, and thus we have core damage after eight hours.

At earlier times during the two types of accidents, water and steam are released through the spargers and the steam is condensed by IRWST water. Due to the hot RCS water and steam condensing, the IRWST water temperature increases without assuming IRWST cooling.

MAAP4 simulation results of hydrogen generation for the sequences [2] are summarized in Table 1. For LOFW-17, steam release starts from 100 seconds into the accident initiation and persists to about 20,000 sec, and hydrogen is released from about 13,000 to 15,000 sec. At earlier steam release phase without hydrogen (100-13,000 sec), IRWST water temperature goes to 390 K (117 °C) and steam average release rate is about 100 kg/sec. During the hydrogen release phase, however, average steam release rate is nearly constant at about 20 kg/sec, and hydrogen release rate is about 0.5 kg/sec and steadily

decreases to zero at about 15,000 sec. The IRWST water is nearly saturated so that condensation of steam discharged during the hydrogen release phase would be inefficient.

Results for SBO-22 is also summarized in Table 1. The major difference from LOFW-17 is that the IRWST water temperature is lower than the case of LOFW-17 since POSRVs are just cycling (opening/closing) at their setpoints and thus the amount of RCS water and steam discharged into IRWST prior to hydrogen release is smaller. However, during hydrogen release, average steam and hydrogen release rates are much greater and they are about 100 kg/sec and 20 ks/sec, respectively.

Based on the result and assuming gas mixture temperature of 1,000 K, the mixture property is calculated at containment design pressure (60 psig). Since steam is a major species of the mixture in mass fraction, thermo-physical properties for only steam are used for simplicity. Given thermo-physical properties and gas inlet flow area, we can calculate gas inlet velocity and turbulence parameters by using Eq.(1)-(4). Boundary conditions thus calculated are shown in Table 2.

Degree of steam condensation is considered based on the IRWST water temperatures obtained from the MAAP4 simulations. For LOFW-17 and SBO-22, IRWST water temperatures are 390 K and 350 K, respectively, during the hydrogen release. Thus much larger steam condensation is expected for SBO-22 sequence. We considered no steam condensation for LOFW-17 (Case A) and 90% for SBO-22 (Case C). A sensitivity case is considered for LOFW-17 with 70% condensation (Case B).

3. Results and Conclusion

Figure 3 show the hydrogen mole fraction distribution in the IRWST freeboard gas space at the time of 10, 20, 30, and 50 seconds after initiation of gas injection for Case A of LOFW-17 (no steam condensing). The gases are nearly homogenized at 50 seconds. Most of the region, hydrogen mole fraction is 18.0%, and is 11.7% only at the outlet vent location. Average hydrogen molar concentration from MAAP4 is about 20%.

For case B of LOFW-17 where 70% of steam from RCS is assumed condensed by the IRWST water, inlet gas mixture flow velocity is reduced due to increased steam condensation. Therefore, the time to mixing is slower than Case A and it is about 150 seconds as shown in Fig. 4. Hydrogen mole fraction is 42.6% through most of the region

and is 7.8% only at the outlet vent side. Average value of hydrogen molar concentration from MAAP4 is about 50%.

For SBO-22 sequence (Case C), the IRWST water temperature is lower than the LOFW-17 (Case A) prior to hydrogen release (350 vs. 390 K). Therefore, the gas mixture inlet velocity is assumed smaller than for LOFW-17 without steam condensation (Case A) even though steam discharge mass flow rate from the RCS is much greater. Steam condensation of 90% is assumed for SBO-22, and thus inlet hydrogen mass fraction is 28.6 %, much larger than Case A and the time to mixing is slower. However, as shown in Fig. 5 most of the region is homogenized in about 100 sec at hydrogen mole fraction of 78.2%. Average value of hydrogen molar concentration from MAAP4 is about 85%.

Three-dimensional mixing behavior of gases in in-containment refueling storage tank (IRWST) of the KNGR is analyzed using the FLUENT to demonstrate applicability of lumped parameter model. The results show that the gases discharged from the RCS under core melting severe accidents are well mixed in a very short time (less than 150 sec) compared with very long hydrogen release duration of several thousands of seconds. In practical situation, considering chemical reactions from HMS and RCS effluent discharge through distributed sparger holes inside the IRWST, the mixing is more efficient than the ideal situation considered in this paper.

It can be thus concluded that the lumped parameter model is reasonably applicable to the engineering design of hydrogen mitigation system, at least with respect to gas mixing phenomena.

References

1. Code of Federal Regulation, 10CFR50.34(f), Post TMI Action Item.
2. KNGR Hydrogen Mitigation System Design, Design Calculation No. 001-END382, Korea Electric Power Corporation.
3. Standard Safety Analysis Report for the Korean Next Generation Reactor (KNGR), Dec. 2000.
4. FLUENT Version 5.4, Fluent Inc.

Table 1. MAAP simulation results for LOFW-17 and SBO-22

	LOFW-17	SBO-22
Steam release duration, sec	100-20,000	40,000-51,000
Hydrogen release duration, sec	13,000-15,000	46,000-51,000
Avg. steam release rate prior to hydrogen release, kg/sec	100	100
Avg. steam release rate during hydrogen release, kg/sec	20	100
Avg. hydrogen release rate, kg/sec	0.5	4
Discharged gas temperature		
IRWST water temperature during hydrogen release, K	390	350

Table 2. Gas mixture flow inlet boundary conditions for FLUENT calculation

Case	LOFW-17		SBO-22
	Case A	Case B	Case C
Degree of Steam Condensing	No	70%	90%
Hydrogen inlet flow rate, m_{H_2} [kg/sec]	0.5 (2.4%)	0.5 (7.7%)	4 (28.6%)
Steam inlet flow rate, m_{H_2O} [kg/sec]	20 (97.6 %)	6 (92.3%)	10 (71.4%)
Velocity, u_{avg} [m/sec]	0.65	0.19	0.32
Turbulence Kinetic Energy, k [m ² /sec ²]	9.35×10^{-4}	1.13×10^{-4}	2.78×10^{-4}
Turbulence Dissipation, ϵ [m ² /sec ³]	1.14×10^{-5}	4.85×10^{-7}	1.85×10^{-6}
Temperature, T [K]	1000	1000	1000

Table 3. Gas mixing characteristics for each cases

Case	LOFW-17		SBO-22
	Case A	Case B	Case C
Time, sec	50	150	100
Minimum hydrogen mole fraction (at outlet vent region), %	11.7	7.8	14.0
Global hydrogen molar fraction, %	18.0	42.6	78.2
MAAP4 average values	~20	~50	~85

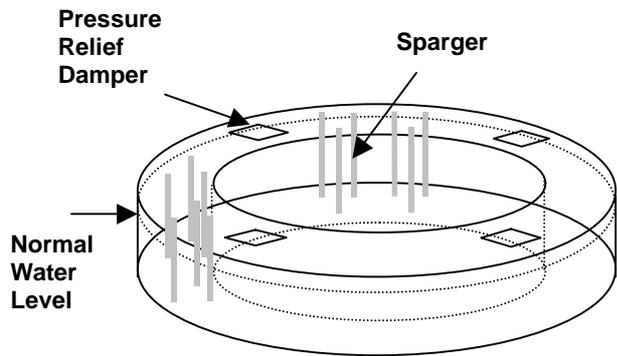


Figure 1. Schematic of the IRWST

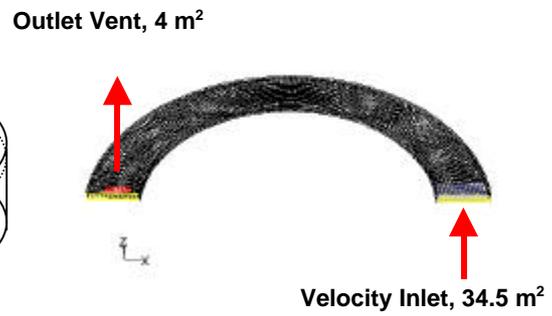


Figure 2. Computational mesh

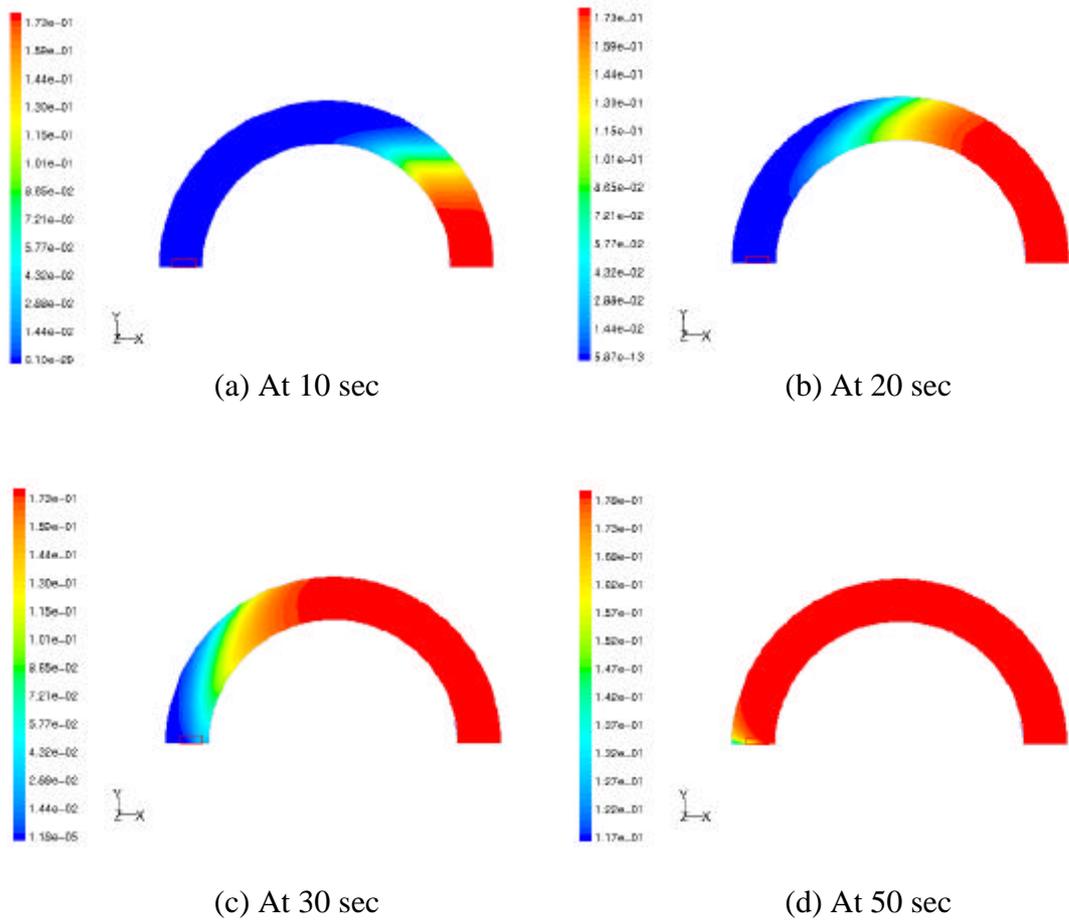
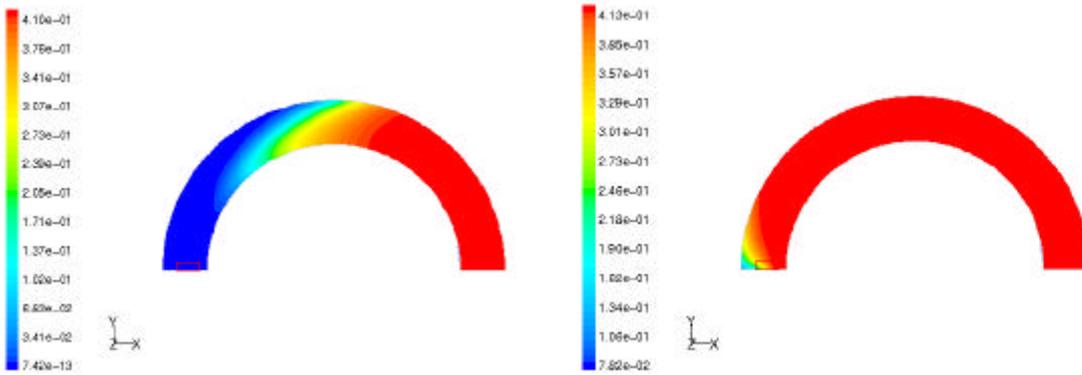


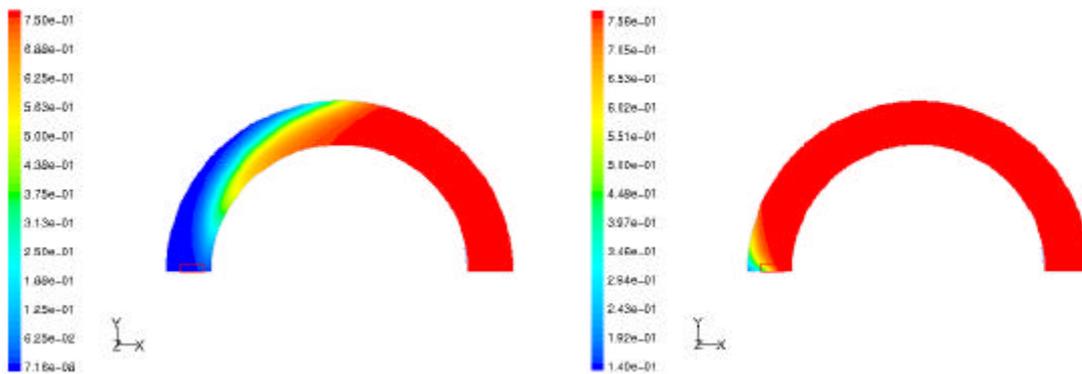
Figure 3. Contours of hydrogen mole fraction for Case A



(a) At 70 sec

(b) At 150 sec

Figure 4. Contours of hydrogen mole fraction for Case B



(a) At 50 sec

(b) At 100 sec

Figure 5. Contours of hydrogen mole fraction for Case C