Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Experimental Study on Hydrogen Behavior at a Subcompartment in the Containment Building

Un-Jang Lee and Goon-Cherl Park

Seoul National University, Korea

ABSTRACT

Hydrogen control during severe accidents has been required by nuclear regulations to ensure the integrity of containment after TMI and Chernobyl accidents. Up to now many experiments have been conducted for the purpose of prevention of hydrogen explosion, which is generated by metal-water reaction during the core-uncovery as well as by virtue of core-concrete interactions after vessel lower head failure. Thus, in this study, experiments have been performed in the SNU hydrogen mixing facility to understand the local behavior of hydrogen mixing and analyze the effects of injection conditions on the mixing at a compartment in the containment building. The facility is a 1/11 linear scaled model of SI injection tank subcompartment in YGN Unit 3&4. Hydrogen was simulated by helium in experiments. Subjected conditions for the test are injection position and direction, mixing ratio, and injection velocity. Also, the effect of condensation through the wall was investigated. Results showed remarkably different local concentrations of He in experiments of several conditions, and the local analysis for hydrogen concentration rather than the lumped compartment analysis, used widely in most plants, would be important to ensure the equipment survivability or to determine the positions of ignitors.

INTRODUCTION

During severe accidents in nuclear power plants, substantial amounts of hydrogen can be generated by the metal-water reaction during the core-uncovery as well as by virtue of core-concrete interactions after vessel lower head failure. Such generated hydrogen may invariably be transported into the containment building and has potential to threaten its integrity by burning. In TMI accident as a real example, 500kg of hydrogen was released and 27psig of peak pressure caused by H_2 burning was measured in the containment. Thus, the hydrogen control has become a big regulatory issue against severe accidents.

Up to now many experiments as well as analytical works for hydrogen management have been conducted around the world to provide the data for computer code development or on burnable limits, and confirm the performance of control measures. Among them, some earlier hydrogen mixing experiments concerned in this study are as follows.

VICTORIA hydrogen distribution experiments in Finland, which modeled a 1/15th-scale model of the Loviisa containment, had examined the hydrogen behavior in an ice condenser containment [1]. The strategy relied on containment-wide natural circulation that develop, once the ice condenser doors are forced open, to effectively produce a well-mixed behavior, and a correspondingly slow rise in hydrogen concentration [2], [3].

In HEDL (Handford Engineering Development Laboratory) they were performed several experiments to investigate potential mixing in the lower compartment of the ice condenser containment. The experiments simulating the dynamic hydrogen release to be possible in degraded-core accidents did result in relatively uniform mixing and in moderate combustion pressures when pre-energized ignitors were used [4], [5].

HDR mixing experiments at Battelle-Frankfurt was conducted for the purpose of the analysis of long-term gas transport behavior in a large-scale, multi-compartment facility in the presence of steam condensation and natural convection conditions. Concentrations were uniform in isothermal tests in a single volume, although distinct gradients were set up in compartments separated by a small orifice [6], [7].

In Japan, in order to obtain their licensing base, NUPEC test was performed in a model containment of 4 loop PWRs. The objective of this test was to investigate hydrogen distribution and mixing behavior in the containment with large volume and many compartments for the case of the relatively large amount of hydrogen production [8], [9].

Most of experiments introduced above were conducted for the inter-compartment analysis of hydrogen concentration distribution for global flow of hydrogen in the large scale and multi-compartment containment building. The key matter of concerns for the experiments were such as containment-wide natural circulation, stratification in some compartment, effective mixing by spray system or diffusion fans, and the effects of hydrogen control system, etc. Results obtained in such experiments provided so far important data to confirm lumped analysis codes, such as MAAP, CONTAIN, MELCOR, which have been widely used for plant analyses. However, such lumped analyses have a limit to meet the requirement of 10CFR50.44(f) which states the local hydrogen limit of 10%, to ensure the equipment survivability and to determine the exact positions of control measures such as ignitor [10] or PAR [11]. Especially if obstacles exist in the way of hydrogen behavior in a compartment which hydrogen diffuses through, those would be expected to cause the remarkable concentration gradient of hydrogen within the compartment. A local concentration peaking as a result of such non-uniform concentration distribution would lead to hydrogen deflagrations and moreover bring a flame flow path, even though the result obtained by the lumped analysis meets the limit.

Thus, in this study, local H_2 concentrations have been measured in a hydrogen mixing chamber to understand the local behavior of hydrogen mixing and, in future, to provide the data for confirming the three dimensional code such as GOTHIC [12] or to be developed if needed. The GOTHIC code is the utility code used for the hydrogen control analysis for YGN 5&6 and next generation reactors in Korea.

EXPERIMENT

Experimental Facility

The mixing chamber used in this experiment is a 1/11 linear scaled model of SI (Safety Injection) tank subcompartment in YGN Unit 3&4. Its height and diameter are about 100cm and 178cm, respectively, and thus the free volume is about 1.34×106 cm^3. The chamber is divided by two layers that simulate compartment layers at 154ft and 169ft in elevation of the plant as shown diagram Fig.1.

The chamber has a ring-type gap between each layer and SI tank which is expected to produce significant three dimensional effects in the points of mixing and flame propagation. Hydrogen was simulated by helium in experiments due to the safety and thus the working fluid was the mixture of He and steam. And the volume amount of injected helium was scaled in the base on that of hydrogen being able to be produced during severe accidents in YGN Unit 3&4.

In this experiment, local He concentrations at 29 points as maximum were measured in various operating conditions. The subjected conditions for the test are injection position and direction, mixing ratio, and injection velocity. Also, the effects of condensation through the wall were investigated. Results showed remarkably different local concentrations of He in several conditions, and thus the local analysis for hydrogen concentration as well as the lumped compartment analysis would be important to ensure the equipment survivability or to determine the positions of ignitors.

Before experiments, the chamber was heated up to the same temperature as the injected mixture to minimize the steam condensation and kept at constant temperature during experiments.

Experiment Condition

The range of operational variables for the test in this experiment is as follows:

Injection amount of mixture: 17.4 lit/min
Velocity of mixture: 57.17 cm/sec
Volumetric injection ratio of helium to steam: 1 / 3.36
Mass flow rate ratio of helium to steam: 1 / 20
Temperature of chamber wall: 80 ℃

Objective of this experiment is to investigate the local mixture behavior and the effect of injection conditions when the mixture is injected at the center of the mixing chamber. Major variables to be tested are followings: injection amount of mixture, mass flow rate of helium and steam, and velocity of the mixture injected into the mixing chamber. Four cases were carried out in this experiment according to the injection condition. Experiment conditions in each case are shown in Table 1, and sampling points are shown in Fig.2.

The injection temperature of steam mixture on the chamber bottom was about 85℃. Then, before experiments, the mixing chamber was preheated up to about 80℃ to prevent the injected steam from condensing on the steel wall. The mixture of helium and steam was injected in the ratio of 1 to 20 in mass. During experiments, two helium detectors were used and each detector was connected to sampling points in the mixing chamber.

In this experiment, the helium behavior due to condensation of steam was also investigated.

Test Results and Discussion

This experiment is an illustration of the mixing behavior at subcompartments in the safety injection tank compartment. Figs. 3 through 6 show results of the local helium concentration measurements and temperature distributions during experiments. The concentrations of all sampling points continue to approach the steady state value in the mixing chamber. Concentration difference at each point is quite large in the lower plenum, even not considering that at the below of the SI tank bottom which has extremely high concentration since the mixture from the injection aperture flows up directly.

In all cases, the concentrations at the gap are higher than those of other points in the lower subcompartment. This result means that the momentum of steam injected into the mixing chamber causes the helium to directly flow up through the gap. Therefore the amount of helium diffused from the injection point is not much compared with that of helium raised by the momentum from the aperture on the mixing chamber.

Fig.3 (b) shows local helium concentration distributions at the intermediate subcompartment. Because the lower gap is a path injected from the lower subcompartment and acts as the source point, the helium concentration at the gap is higher than at other detection points. Above this point, the concentration distribution shows uniform.

As the injection amount of helium and steam increases, the relative mixing is enhanced as shown in Fig.4. Because large increase of the injection amount did reduce relatively amount of the air in the lower subcompartment, the concentration distribution of case 1A3 is higher than that of case 1A1. However, due to larger injection amount, the mixing in the lower compartment is delayed a little compared to the first case, except around the safety injection tank. And, in the intermediate subcompartment, non-uniform mixing is observed similar as in the first case due to larger amount of injection through the gap.

Fig.5 shows the effect due to the condensation through the walls of the chamber and SI tank. Although the temperature difference of about 30℃ with the case 1A1 and 1B1 resulted in little increase of helium concentration, the condensation of the injected steam induced well-mixing in the lower subcompartment, especially with reducing the concentration at the gap. There is reason in these results since the inertia and buoyancy of steam became weak due to the condensation through the walls, and the horizontal gas diffusion in the lower subcompartment dominated. That can be also a good explanation for same trend at the intermediate subcompartment of Figs. 3(b) and 5(b) where the momentum of steam already loses its power whether there is condensation or not. Lastly, the increase of injection velocity of the mixture also causes the well and earlier mixing in the lower subcompartment due to increased turbulence, as shown in Fig.6.

CONCLUSIONS

For hydrogen management in severe accidents with degraded nuclear core of PWR's, several experiments have been performed in the SNU hydrogen mixing facility. The SNU test facility represents a compartment of a 1/11 linear scaled model of the safety injection tank compartment in YGN Unit 3&4. From the experiments injected symmetrically into the test chamber we could understand the behavior of helium mixture according to the effects of obstacles in the SI tank compartment.

In this experiment in which the helium mixture was injected symmetrically the change of the injection amount and velocity did hardly affect the entire behavior of helium mixture in the subcompartments. But when the amount and velocity of injected mixture was increased, approach to the steady state of each sampling point was delayed. The helium concentration measured at the intermediate subcompartment was very low. From the experiment, it could be concluded that in experiments injected at the high injection rate, the mixture was mixed well in the atmosphere of the lower subcompartment except the vicinity of injection point. At a viewpoint of hydrogen behavior the effects of a specific geometry at a compartment in the containment building and the relative local distribution of hydrogen concentration are considered in this experiment. However, at a viewpoint of hydrogen mixing scaling, there are some limits to regard the concentration distribution from SNU experiments as the hydrogen behavior in real plants. In this point the very principal factor is to be impossible to define quantitatively the amount of hydrogen, which transports in the SI tank compartment in accidents. However long term generation of hydrogen such as during MCCI should be seriously considered because of large local concentration difference in the experiment of the low injection rate. And the hydrogen behavior at the gaps in the SI tank compartment should be considered carefully because local concentration peaking by non-uniform path of hydrogen may occur and develop to the trace of flame propagation. In future, the data from this study will be provided in confirming the capability of the three dimensional code.

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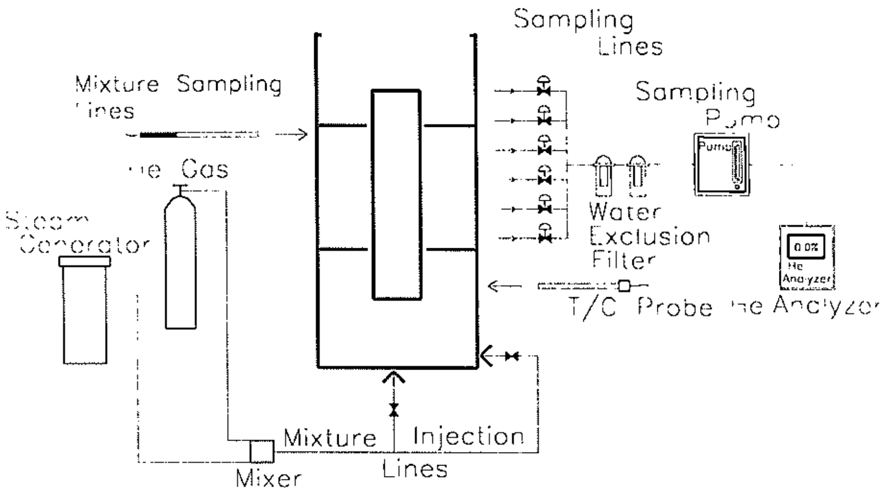


Fig.1 Configuration of SNU Hydrogen Mixing Facility

Test / Condition	Cases			
	1A1,1B1	1A3,1B3	1A4,1B4	1A5,1B5
Helium (g/min)	0.4	0.72	0.4	0.4
Steam (g/min)	8	14.5	8	8
mixture injection velocity (cm/sec)	57	101	57	220
mixture injection (lit/min)	17.4	30.4	17.4	17.4
mixing chamber wall temp.(℃)	80	80	30	80

Table 1. Test Condition of Case 1, 3, 4, and 5

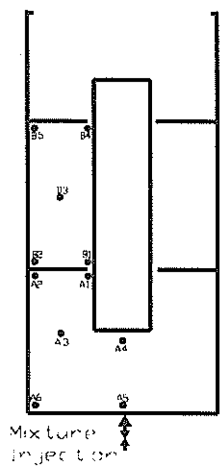
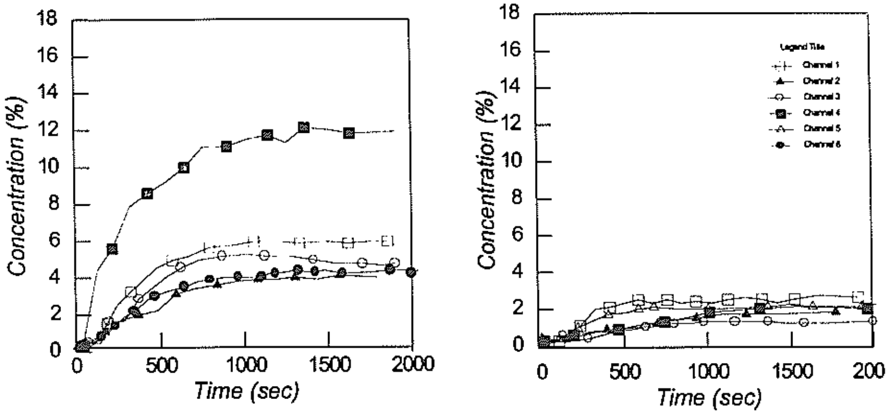
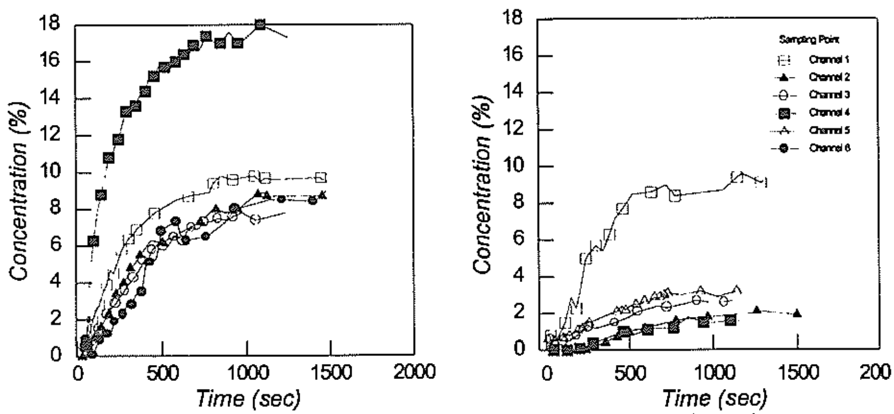


Fig.2 Sampling points



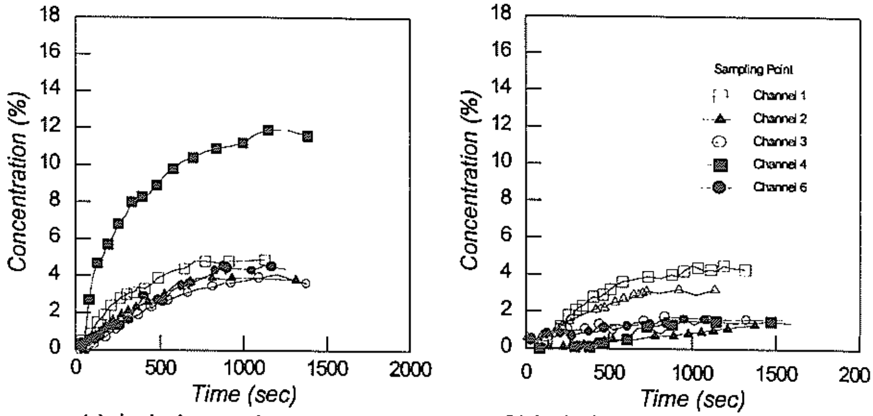
(a) in the lower subcompartment (b) in the intermediate subcompartment

Fig.3 He Concentration Distribution of Case 1A1,1B1



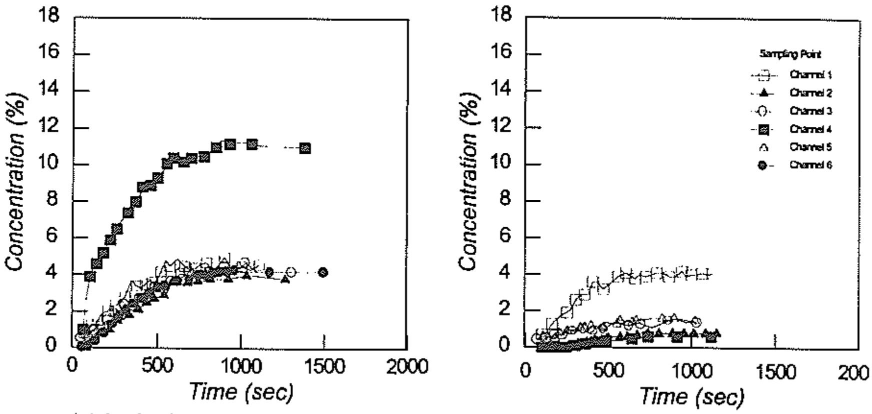
(A) In the lower subcompartment (b) In the intermediate subcompartment

Fig.4 He Concentration Distribution of Case 1A3, 1B3



(a) in the lower subcompartment
(b) in the intermediate subcompartment

Fig.5 He Concentration Distribution of Case 1A4,1B4



(a) In the lower subcompartment
(b) In the intermediate subcompartment

Fig.6 He Concentration Distribution of Case 1A5,1B5