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Thermal Stratification during Atmospheric Stabilization in a Containment Leakage Rate Test

Han-Chul Kim [a,b*], Su-Kyoung Pak [a], Jun-Soo Lee [a], Ku-Young Chung [a], Seon-Oh Yu [a]
[a]*Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 34142*
[b]*Dept. of Mechanical and Control System Engr., Handong Global Univ., 558, Handong-ro, Heunghae-eup, Buk-gu, Pohang-si, Gyeongsangbuk-do, Korea*
[*]*Corresponding author: khc@kins.re.kr*

1. Introduction

Hydrogen combustion accompanied by core damage is one of realistic challenges to the containment integrity as it was demonstrated in the Fukushima Daiichi accident. In order to perform appropriate accident management actions under such circumstance, it is important to accurately predict the local gas distribution in the containment. Since thermal stratification limits gas mixing, it has been the objectives of several research projects organized by the OECD Nuclear Energy Agency (NEA) [1, 2]. At the same time, the capability of the Lumped Parameter (LP) and Computational Fluid Dynamics (CFD) codes in the area of containment thermal hydraulics and atmospheric gas/steam distribution has been assessed through various benchmarks including the international standard problems.

TOSQAN, MISTRA and THAI experiments which were carried out as parts of the ISP-47 exercise showed that thermal stratification was established after injection of hot helium, steam or air. The LP codes, which are currently the main tools for containment thermal-hydraulic analysis, showed the spread of the results about gas temperature and concentration profiles due to user effects and some limitations in the applied simplified model description. The authors suggested 'a common international activity to perform generic plant application exercise to study nodalisation effects, impact of steam and light gas injection etc. based on a generic (probably simplified) PWR containment.' [2]

An integrated leakage rate test (ILRT) of the containment, performed to validate the assumptions taken for the calculations of the offsite consequence following a reactor accident, could provide useful information that may partly meet the purposes suggested as above. In this study, we examined the thermal stratification phenomena during an ILRT performed at a CANDU 6 plant in Korea, and then simulated them using the MELCOR 1.8.6 code [3, 4] and the plant input model developed by the Korea Institute of Nuclear Safety (KINS) [5, 6, 7, 8].

2. Containment integrated leakage rate test

In Korea, the domestic regulatory requirements [9] demand that a preoperational ILRT and subsequent periodic tests be conducted for NPPs at not less than 96% of the accident pressure every five years. The acceptance criterion for the tests is that the integrated leakage rate shall not exceed 75% of the maximum allowable value (L_a) at the test pressure. The Korea Hydro & Nuclear Power Co., Ltd. (KHNP) is responsible for conducting ILRTs of its own NPPs, and the activities are inspected by KINS. The test includes various phases: pressurization, atmosphere stabilization, measurement of the overall leakage rate, and a verification test followed by depressurization. Fig. 1 shows the normalized pressure during the entire period of the test. Among the test phases of the selected test, we chose to simulate the atmosphere stabilization and the main test phases.

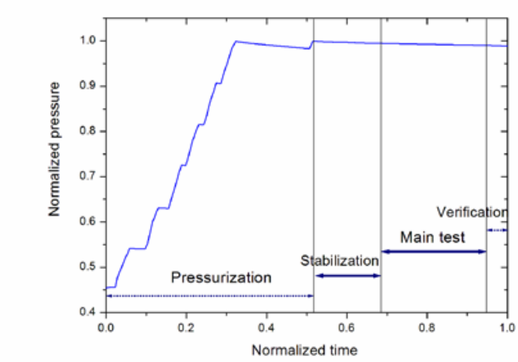

Fig. 1. Containment pressure history during the entire test period in normalized form.

Figure 2 shows the measured containment pressure in the selected period. They show a continuous pressure decrease from the beginning stage, which was followed by an inflection point when the lamps in the containment building were turned off. A rapid transient in the beginning seemed to be caused by relatively strong momentum-driven flows just after the last pressurization stage.

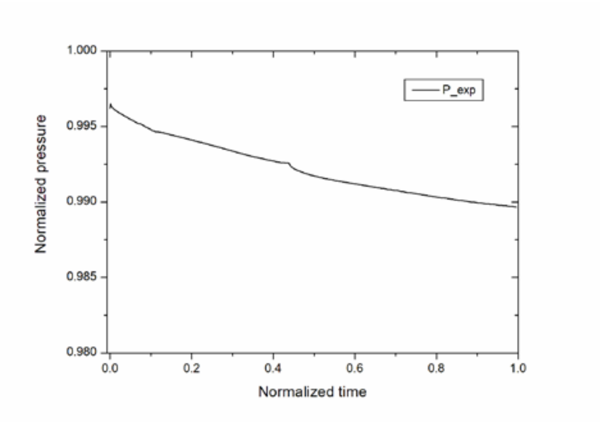

Fig. 2. Measured containment pressure during the test.

Figure 3 shows the measured temperature distribution in the containment, where the average is described in circles. Momentum-driven flows due to the injection of relatively hot air during the pressurization period immediately before the beginning of the stabilization period might also serve to decrease the pressure and temperature in the beginning stage. In this figure the thermal stratification in the containment building was maintained during the entire test period or even strengthened as time went by, despite the fact that local mixing appeared in the upper region. A slow temperature change shows convergence with time evolution in the upper free-volume region, while in the bottom region, where there are mainly separate compartments, the temperature diverged increasingly from that of the main stream. It appears that a buoyancy-driven flow and the associated atmosphere entrainment were greatly restricted in the lower compartments.

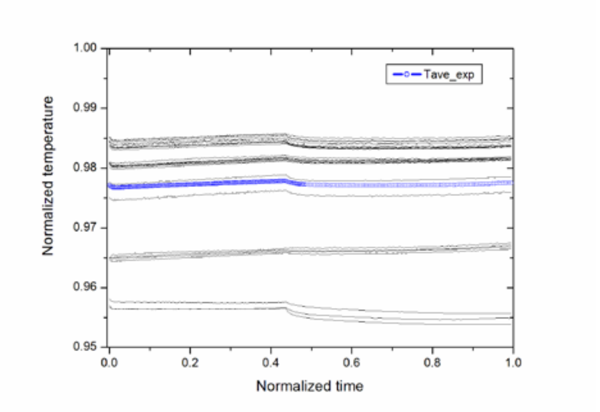

Fig. 3. Measured temperature distribution in the containment during the second test.

3. Analysis methods and results

The MELCOR model for the CANDU 6 containment with 51 control volumes, 102 flow paths and 257 heat structures [8, 9] is shown in Fig. 4.

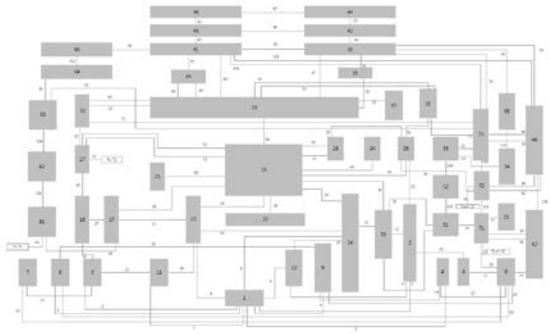

Fig. 4. Containment model.

The analyses of the test resulted in overestimations of the containment pressure, as shown in Fig. 5. The analysis of the containment temperature, shown in Fig. 6, resulted in slight underestimations, which is contrary to the pressure estimations. A small drop at the beginning accompanied by a very slow decrease afterwards is noticeable in the analysis, perhaps due to the unsteady-state start of the calculation and modeling limitations. Compared with the measurements shown in Fig. 3, the estimations show that mixing in the upper region was weaker, whereas thermal stratification appeared to be less severe in the lower and bottom regions.

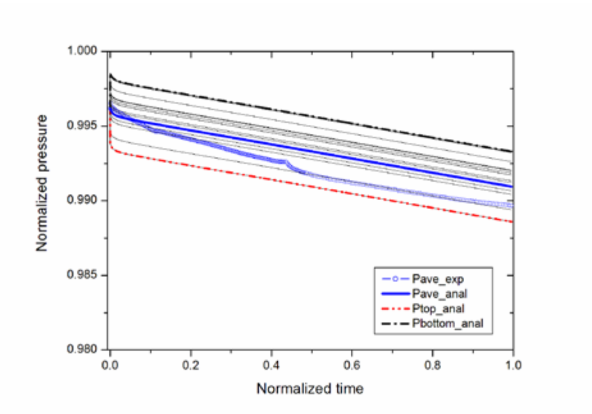

Fig. 5. Calculated containment pressure: comparison with the test data.

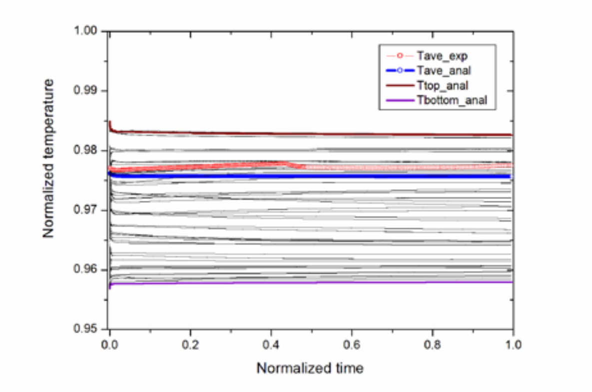

Fig. 6. Estimated temperature distribution in the containment during the test.

Comparisons of the axial temperature distribution in the containment atmosphere between the measurement and estimation at the beginning and at the end of the test are shown in Figs. 7 and 8, respectively. In Fig. 7 inappropriate modeling of the initial temperature distribution is shown in the middle and bottom regions, where measurement locations were quite less than the number of compartments in the input model. Figure 8 shows that thermal stratification at the end of the test was estimated reasonably, however, it slightly underestimated the spread of stratification.

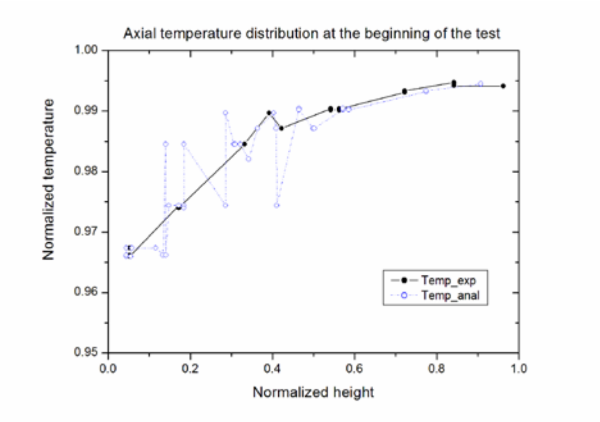

Fig. 7. Calculated axial containment temperature at the beginning of the test: comparison with the test data

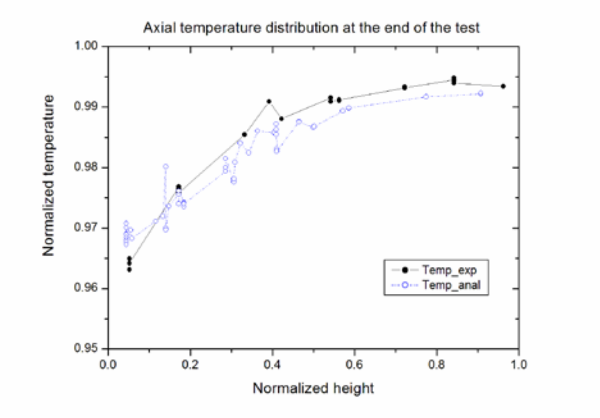

Fig. 8. Calculated axial containment temperature at the end of the test: comparison with the test data

Further comparisons of the local temperatures between the measurement and analysis of the test were done for the top (CV43: steam generator room) and bottom (CV1: access area) regions. Figures 9 and 10 show the temperature at the top and in the bottom, respectively, for which the maximum deviations from the measurement were -0.656K and +2.146K, respectively, at the end of the test. It seems that difficulties in the modeling of the thermal-hydraulic characteristics including the parameters related to flow paths in the lower compartment region, together with the limitation of the lumped parameter model's ability, affected these deviations. Since the upper region occupies most of the free volume in the containment, the average temperature shows a deviation from the measurements less than the large local deviations, as shown in Fig. 6. Therefore, when the thermal-hydraulic condition and the gas/steam distribution in the containment are analyzed, this limitation in estimating thermal stratification should be considered.

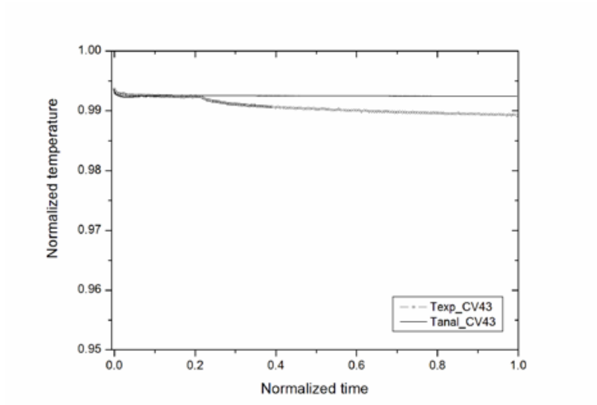

Fig. 9. Calculated local temperature in the top region (CV43: steam generator room): comparison with the test data.

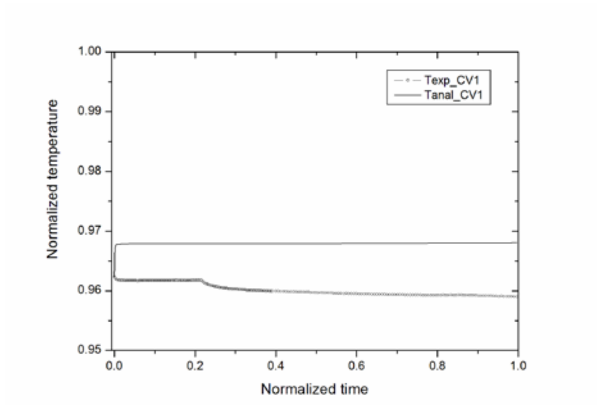

Fig. 10. Calculated local temperature in the bottom region (CV1: access area): comparison with the test data.

4. Conclusions

Thermal stratification in the containment following the stabilization period of an ILRT performed at a CANDU 6 plant was examined. This phenomenon was observed to be maintained during the entire test period or even strengthened as time went by, although local mixing appeared in the upper free-volume region. A MELCOR 1.8.6 simulation of the test shows a slightly weaker thermal stratification. Especially, in the lower region which have many compartments, the estimated local atmosphere temperature shows a significant deviation from the measurement. Therefore, the limitation in estimating thermal stratification should be considered in the prediction of the thermal-hydraulic variables and atmospheric gas or steam distribution in the containment after an injection of gas or steam into it during a severe accident.

Acknowledgments

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