Summary of the Research Project on Horizontal Heat Exchanger for PCCS

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Abstract

This paper summarizes the study on the horizontal heat exchanger for a passive containment cooling system (PCCS) for the BWR conducted at the Japan Atomic Energy Research Institute (JAERI). The PCCS is utilized in the various BWR designs including SBWR, ESBWR and ABWR-II to passively cool the containment during accidents. Two experimental facilities were used for this research project: the first one for obtaining better understandings on fundamental thermal-hydraulic behavior in a single horizontal condenser-tube, and the second one for confirming the integral performance of the horizontal heat exchanger. By using the data obtained from those facilities, heat transfer models were developed for condensation and heat transfer deterioration under the presence of noncondensable gas. The newly developed and validated heat transfer models were incorporated into a newly-developed system analysis code based on the RELAP5 and ACE-3D codes, which successfully predicted detail two-phase flow behavior both in the primary and secondary sides of the PCCS heat exchanger. Furthermore, the effectiveness of the horizontal PCCS was confirmed through the analysis of typical severe accident scenarios at the BWR. The research project was successfully completed by establishing the prediction methods for the PCCS performance and confirming its effectiveness through the experimental and analytical results.

1. INTRODUCTION

The passive containment cooling system (PCCS) is a system that passively removes heat from the containment to the liquid pool surrounding the PCCS heat exchangers (HEXs) [1-3]. The application of the PCCS to the nuclear power plant design was first proposed by the General Electric company for the SBWR design, where the PCCS is used not only to cool the containment but also to provide condensed water to the core through the gravity-driven injection system (GDIS). The GE's developed PCCS utilizes the HEX that consists of straight vertical heat transfer tubes having a relatively large diameter of ~50 mm, and large header pipes at the inlet and outlet of the tubes. The inlet header of the heat exchanger is connected to the drywell, and the outlet header is connected to the GDIS for the safety injection, and the pressure suppression pool for the noncondensable gas vent. This configuration enables the passive long term core cooling without depending on the active components and thus establishes a very reliable system.

The other application for the PCCS has been proposed by the Japanese industries for the ABWR-II as described in the previous section of this report. For this design concept, the PCCS has only a function of the heat removal from the containment during severe accidents with failures of the active safety systems. This system concept is illustrated in Fig.1: the PCCS heat exchanger is connected to the dry well for the inlet side and the suppression pool for the outlet side. Liquid water is supplied to the containment bottom region from the suppression chamber using some accident management measures in case that the core melt is ejected from the pressure vessel.

The research project on the PCCS started in 1998 at JAERI with collaboration from the Japanese industry. In this project, the use of the horizontal HEX was proposed for the PCCS because of the following advantages over the vertical one:

1) The heat exchanger's geometry such as tube diameter, pitch, and length can be optimized based solely on the heat transfer performance. For the vertical heat exchanger, the tube length is limited by the water level in the PCCS pool, and the tube diameter is limited also by the requirement for the earthquake resistance because the tubes also have a function of the structure support for the large and heavy inlet header pipe locating above the tube bundle. These advantages enable the horizontal HEX to be more compact.
2) The horizontal HEX can be submerged in the PCCS pool with lower liquid level compared to that for the vertical one, which enables the more efficient use of the pool water inventory.
3) The maintenance and inspection of the PCCS components can be much easier because the inlet and outlet plenums can be placed outside the PCCS pool.

The design condition of the PCCS is determined from the required function to maintain the containment integrity for at least one day during severe accidents with failures of the active safety systems. Since it is well known that the containment failure due to the overpressurization occurs at pressure of much higher than the design pressure, the pressure of 0.7 MPa is used as the reference pressure for the PCCS design, which is a relatively conservative value as a threshold of the containment failure. The reference inlet steam flow rate is the 1 % of the nominal core power, which is a typical decay heat level during the long term core cooling phase. Furthermore, the PCCS of this concept should be functional even under the presence of some degree of the noncondensable gas because the noncondensable gas is likely to be generated through various chemical processes during severe accidents. The reference inlet noncondensable-gas quality of 1% is determined from this requirement. These requirements constitute both the PCCS design specification and the reference conditions for the experiments.

The program consisted of experiments using two facilities for fundamental thermal-hydraulic investigation and integral confirmation, the validation and modification of the analysis codes, and the system analysis for the BWR severe accidents. Those are described in the followings in this paper.

2. FUNDAMENTAL THERMAL-HYDRAULIC EXPERIMENT

A fundamental thermal-hydraulic experiment was conducted to obtain better understandings on heat transfer and condensing two-phase flow in a U-shaped horizontal tube[4,5]. The tested tube geometry is a U-tube that can be placed in the vertical plane; the flow direction inside the U-tube is horizontal for the straight sections and downward for the bend section. The tube is contained in the outer tube to cool the outer surface of the tested tube by single-phase liquid flow. The outer tube is divided into several sections having an instrumented water supply system so that the local heat transfer rate can be measured for each section. The tested thermal-hydraulic parameters include the velocity of vapor and gas mixture at the inlet, the system pressure, and the non-condensable gas quality.

The measured heat transfer coefficients were compared with existing heat transfer correlations. In general, existing correlations showed poor agreements especially for the condensation heat transfer in the annular flow regime and the heat transfer deterioration by the presence of noncondensable gas. The figure 2 shows the comparison of the predictions with existing and newly developed correlations, and the experimental data for the annular flow regime at pressure of 0.7 MPa. The figure shows that the Shah model used in the RELAP5 code underpredicts the heat transfer coefficients. The newly developed condensation correlation is based on the measured linear relationship between the heat transfer coefficient and the roll wave passing frequency along the inner surface of the tube, which shows better agreements[6]. From those investigations, a heat transfer package consisting of newly-developed and validated correlations was established for the improvement of the RELAP5 code[7].

3. LARGE-SCALE EXPERIMENT

The purposes of the large-scale experiment were to 1) confirm the performance of the horizontal heat exchanger under the reference conditions mentioned previously, 2) investigate effects of the multi-channel tubes in the primary side and the multi-dimensional boiling flow in the secondary side, and 3) validate the analysis codes[8,9,10]. The test section consisted of a tube bundle which was a halved, full height, prototypical-scale bundle, and a secondary pool. The tube length was typically 8m from the inlet to the outlet. The electric power of up to 10 MW was used for the steam supply to the facility. The water supply to the PCCS pool was controlled to keep the collapsed level above the tube bundle. The pool gas phase was connected to atmosphere through several large nozzles so that the pressure was kept approximately at atmospheric level. The void fraction distribution in the secondary side was measured by traversing optical void probes between the half and top elevation of the bundle.

The onset of boiling was observed in the lowest tubes of the upper tube bundle, that is, the lower tube bundle was cooled only by single-phase liquid flow for typical test conditions. The flow regime transition from bubbly to churn flow occurred in the upper bundle with increase in the elevation. The measured heat transfer coefficient for the tube outer surface increased with the increase in the void fraction in the upward direction. The magnitude of the increase, however, was not enough to differentiate the total heat transfer rate among the tubes, because the other heat transfer resistances at the tube inner surface and through the wall were not affected by the flow regime transition in the secondary side. Heat transfer deterioration due to the formation of vapor blanket around the tubes was not observed for the present test conditions.

The primary side flow rates were stable for the reference conditions, and became oscillatory when the primary pressure was relatively low due to insufficient condensation. Since the gaseous flow from the outlet plenum was directly discharged to atmosphere through the vent line for the present test configuration, such insufficient condensation did not affect the pressure response, which would have increased the primary pressure if the system consisted of a closed loop as for the actual reactor. The effect, however, is insignificant because the primary pressure increase is suppressed by the increase of the condensation rate, establishing a new balanced condition at a higher pressure. The present experimental data have indicated that the entire vapor is condensed in the tubes before the pressure reaches the reference pressure of 0.7 MPa.

4. CODE DEVELOPMENT

A new code for the detailed analysis was developed using two codes: RELAP5 and ACE-3D that is an analysis code for the multi-dimensional two-phase flow developed at JAERI[11]. The RELAP5 code calculates the primary side behavior; the ACE-3D calculates the secondary side. Typical validation results for the code are shown in Figs. 3 and 4, where the prediction results are compared with the measured distribution of the quality in the condenser tubes and the void fractions in the bundle side. The calculation successfully predicted the uniform quality distribution inside the tubes with the multi-dimensional boiling behavior in the secondary side as was observed in the experiments.

Sine this code takes a relatively long calculation time, a simplified RELAP5 noding model of the horizontal heat exchanger was developed for efficient and economical system analysis, where the RELAP5 was modified using the heat transfer package developed in this study. In this analysis, the heat exchanger is modeled with a single tube based on the experimental result of uniform condensation behavior among the tubes. The evaluation results showed that the simplified model predicted well the total heat removal rate and pressure drop across the heat exchanger for all the tested conditions.

5. SYSTEM ANALYSIS

The system analysis was performed using the simple noding model and the RELAP5 code modified using the heat transfer packager developed in this study[12]. The objective of this analysis was to confirm the performance of the PCCS with the horizontal heat exchanger in preventing the containment failure for at least one day. Since the RELAP5 cannot predict the generation of non-condensable gas by the chemical reactions such as molten core concrete interaction (MCCI) during severe accidents, the MELCOR code (version 1.8.5) was used to evaluate the gas generation rate. The MELCOR results were imposed by using the time-dependent volumes and junctions components in the RELAP5 code. The RELAP5 calculation started at the onset time of ejection of the core melt from the reactor pressure vessel bottom. It is conservatively assumed that the containment is filled completely with non-condensable gas at this time.

The two calculated drywell pressures are shown in Fig.5 for the scenario of the transient without the ECCS injection (TQUV), where two cases corresponded to the calculations with and without the PCCS. The figure clearly indicates the effects of the PCCS heat removal; the containment pressure increased beyond the reference pressure of 0.7 MPa for the case without the PCCS at 50000sec, and was kept below the pressure limit for more than 100000 sec for the case with the PCCS. This result confirms the effectiveness of the PCCS to prevent the containment failure for at least 1 day for this scenario (= 86400 s).

6. CONCLUSIONS

The research project was conducted at JAERI to clarify the applicability of the passive containment cooling system (PCCS) with horizontal heat exchangers to a next-generation BWR. The design requirement of the PCCS of this concept is to prevent the containment damage due to pressurization for at least one day during severe accidents with failures of the active safety systems. The research program consisted of the fundamental thermal-hydraulic experiments, the bundle experiments, the code validation and modification, and the reactor analyses with the modified code.

The fundamental thermal-hydraulic experiments were performed first to investigate the performance of a horizontal condenser tube under wide ranges of experimental conditions. Experimental results have shown that the condensation heat transfer coefficients for the annular flow regime are underpredicted by existing correlations. A new model was developed, which was based on the measured relationship between roll wave passing frequencies and the heat transfer rates. The new correlation predicted well the experimental data.

The large-scale experiments were performed secondly to confirm the total performance of the horizontal heat exchanger and to validate analysis codes to predict overall thermal-hydraulic behavior of the horizontal HEX. Various flow regimes were observed in the secondary side of the tube bundle including single-phase liquid, bubbly, and churn flows with the increase in the elevation in the tube bundle. Effects of such flow regime transition, however, were not large enough to differentiate the heat transfer rates among tubes. No instability was observed for the present test conditions.

A code to predict the detail behavior at the PCCS HEX was newly developed by using the RELAP5 code for the primary side calculation and the ACE-3D for the bundle side calculation. The RELAP5 code was modified by adding the heat transfer package developed in this study. The developed code agreed well with the measured quality distribution inside the tube and void distribution in the tube bundle.

The BWR severe accidents were analyzed assuming failures of all the active safety systems by using the modified RELAP5 code. The results has confirmed that the design target of the PCCS is clearly satisfied; that is, the containment pressure is kept below the reference pressure of 0.7 MPa, and the containment is not damaged on a large scale by pressurization during severe accidents for at least one day even when all the active safety systems are failed.

ACKNOWLEDGEMENTS

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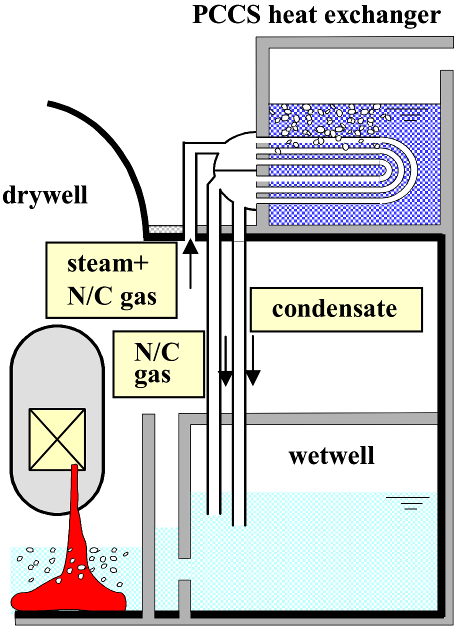

Fig. 1 Schematic view of PCCS actuation

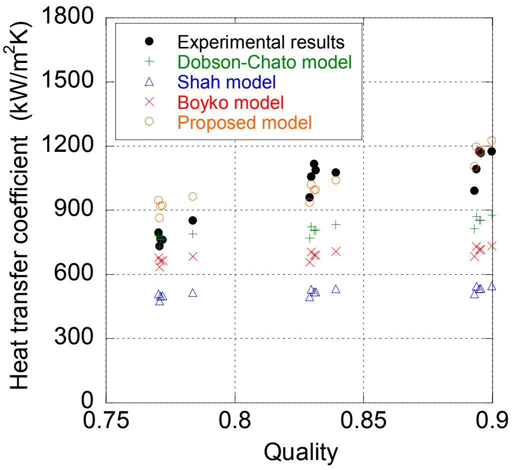

Fig. 2 Comparison of the experimental data and predictions with existing and proposed

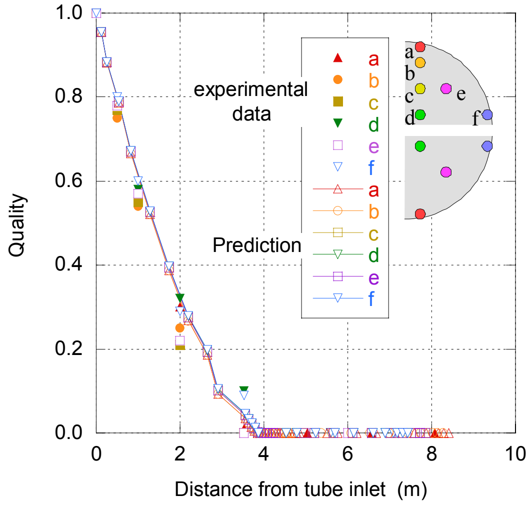

Fig. 3 Comparison of quality distribution at reference

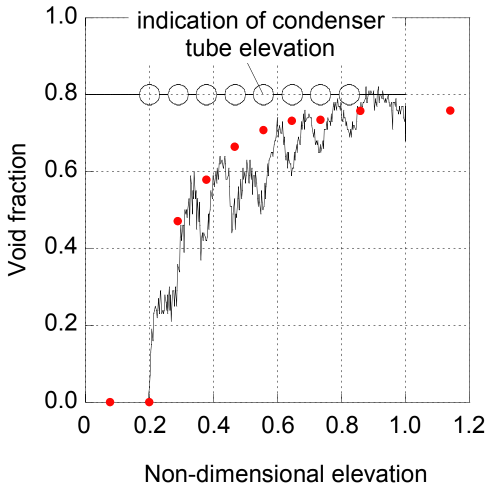

Fig. 4 Void fraction distribution in tube bundle

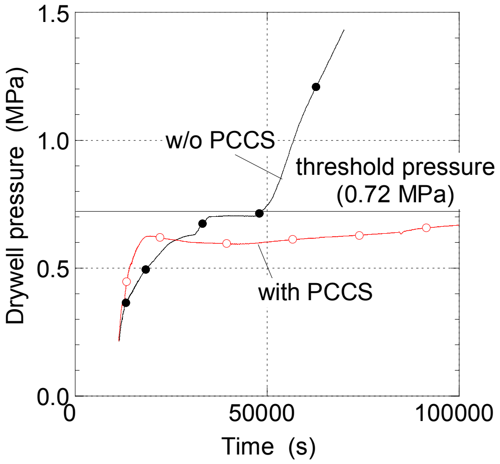

Fig.5 Drywell pressure behavior with and without PCCS