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Analysis of Boiling Instability in Natural Circulation Conditions in Multiple Tube using the TRACE Code

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1. Introduction

After the Fukushima accident, importance of passive safety systems that doesn't use electric energy was emphasized [1]. For this reason, as a means of passive decompression system, Filtered Containment Venting System (FCVS) is introduced for operating nuclear power plants (NPPs) in various countries. However, the use of FCVS inevitably releases radioactive materials from containment atmosphere to environments and so it cannot be ultimate solution. Therefore, the introduction of Passive Containment Coolant System (PCCS) for operating NPPs should be considered to cope with FCVS. The PCCS removes the high energy inside the containment building utilizing the natural circulation and condensation without releasing radioactive material into the environment [2]. The schematic of PCCS is shown in Fig. 1.

Currently, the concept of PCCS take aim the developing NPPs in Republic of Korea. Therefore, when PCCS is installed, it is not necessary to consider the space restraints and boiling phenomenon inside the heat transfer tubes of PCCS. However, to apply the PCCS on operating power plant, the space restraints must be considered indispensable. Thus, the capacity of PCCS should be as compact as possible.

For a compact design, the heat transfer tube should be as dense as possible, and the heat transfer efficiency should be increased utilizing the boiling phenomenon inside the heat transfer tube.

Due to coolant boiling, the natural convection instability such as flow reversal may occur, and it leads to degradation of heat removal. Therefore, the natural convection instability inside the tube when coolant boiling occurs should be considered.

In this paper, we analyzed the boiling instability under natural circulation conditions in multiple tubes by using TRACE code.

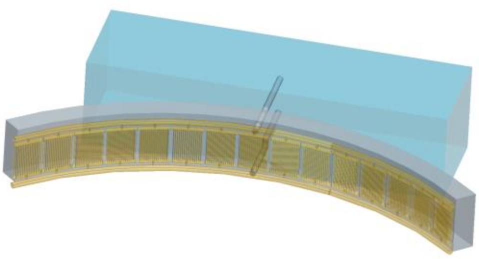


Fig. 1. The schematic of PCCS

2. Methods and results

2.1 Passive Containment Cooling System (PCCS) Model

To analyze the instability inside the tubes, the TRACE which is the thermal-hydraulic analysis code was used [3]. The nodalization of PCCS is showed in Fig. 2. As shown in Fig. 2, the 17 control volumes (CV) are modeled to calculate the thermal-hydraulic analysis. The Passive Containment Cooling Tank (PCCT) is modeled as a CV200, and the pipes which are connected the tubes of PCCS with PCCX are modeled as CV120, CV140 and CV160. We assumed that there are three tubes in PCCS to analyze the boiling instability depending on thermal boundary condition. Additionally, the atmosphere is modeled as a CV200 to maintain the constant pressure.

The heat structures are modeled to heat the multiple tubes. Except the multiple tubes and the atmosphere, all control volumes are assumed as adiabatic condition.

In this paper, we did not consider the condensation of the outer surface of multiple tubes to simplify the calculation.

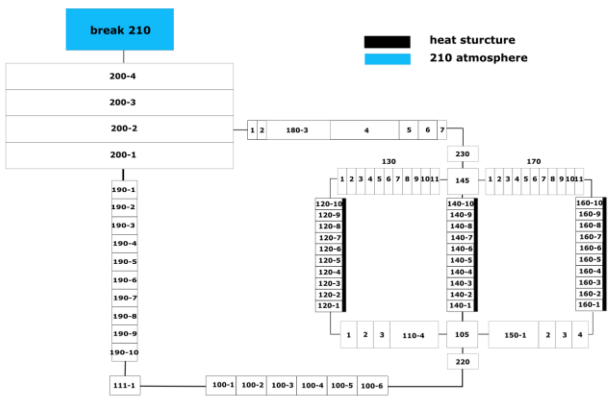


Fig. 2. PCCS nodalization

2.2 Case Study depending on thermal boundary condition

Depending on the arrangement and position of the heat exchanger tube assemblies in PCCS, the heat transfer in tubes is different due to the difference of temperature distribution by screen effect or suction effect. Also, when severe accident occurs, the aerosols are distributed in containment atmosphere. The aerosol could be deposited on the tubes resulting in degradation of PCCS performance with different fouling effect [4]. As a result, the thermal boundary condition on the tubes could be different. It makes the difference of heat transfer coefficient for each tube which induces different mass flow rate of natural convection in PCCS. Also, the boiling instability of the multiple tubes would increase, and the backflow would be induced.

To investigate the phenomenon related with instability of PCCS depending on heat condition, three cases were compared. Given heat to the multiple tubes was assumed as constant heat, 10 kW. The total amount of heat is different for three cases as summarized in Table I.

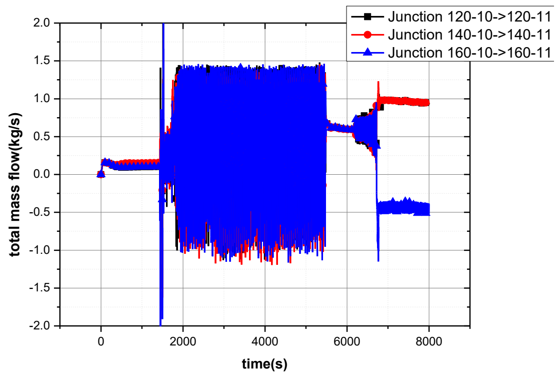
The detailed description for three cases as follows:

- Case 1: The constant heat, 10 kW, is applied to all three tubes (Total power: 30 kW).
- Case 2: The constant heat, 10 kW, is applied to one tube which is located in middle, CV140 (Total power: 10 kW).
- Case 3: The constant heat, 10 kW, is applied to tube tubes which are located in side, CV120 and CV160 (Total power: 20 kW).

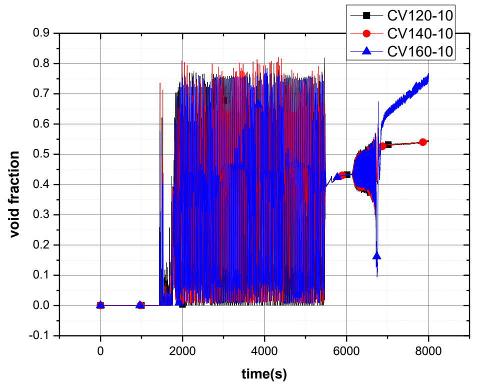
Table I. Summary of the cases

Case Description	CV120 (Tube 1)	CV140 (Tube 2)	CV160 (Tube 3)
	The amount of heat given to each tube		
Case 1	10 kW	10 kW	10 kW
Case 2	0 kW	10 kW	0 kW
Case 3	10kW	0 kW	10kW

2.3 Case 1 results



(a)

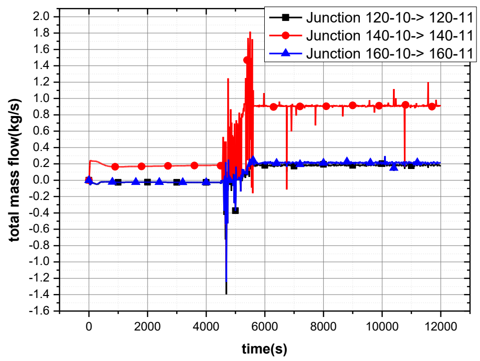


(b)

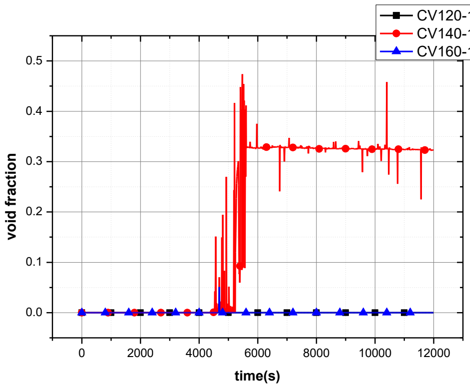
Fig. 3. (a) Combined liquid and vapor flow rate (top junction of the CV120, CV140, CV160 tubes)
(b) Vapor volume fraction (top control volume of CV120, CV140, CV160 tubes)

The case 1, which is the single-phase condition, the mass flow rate of the three-multiple tube have a similar behavior. Thereafter, a large oscillation is observed when boiling occurs in all three tubes, proving the boiling instability of two phase flow. The void fraction of case 1, the flow regime is different with that of case 2 and case 3, due to difference of void fraction.

2.4 Case 2 results



(a)

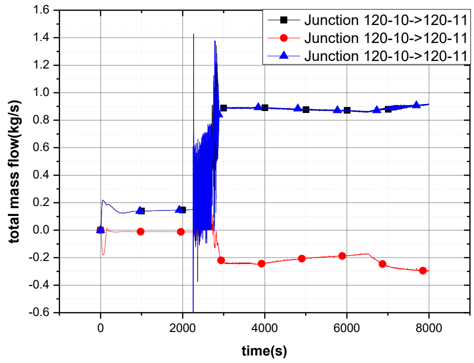


(b)

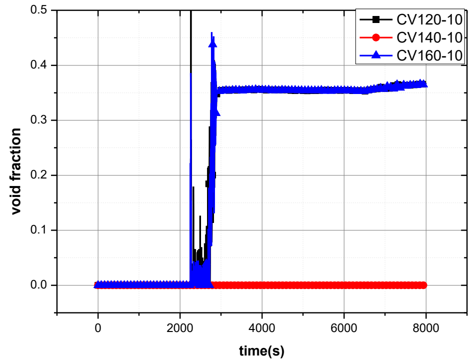
Fig. 4. (a) Combined liquid and vapor flow rate (top junction of the CV120, CV140, CV160 tubes)
(b) Vapor volume fraction (top control volume of CV120, CV140, CV160 tubes)

In the case 2, which is depicted in fig. 4 (a), constant back flow was observed in CV120, CV160 tubes which is in the single-phase condition. When the two-phase flow occurs in CV140 tube, mass flow rate rapidly increases in CV140 tube. At that moment, back flow phenomenon is observed in CV120, CV160 tubes by the boiling instability. The case1 shows a strong boiling instability due to sharp vibrations. However, in the case2, the void fraction increases rapidly, eventually entering slug flow pattern and stabilized.

2.5 Case 3 results



(a)



(b)

Fig. 5. (a) Combined liquid and vapor flow rate (top junction of the CV120, CV140, CV160 tubes)
(b) Vapor volume fraction (top control volume of CV120, CV140, CV160 tubes)

The backflow phenomenon observed at the top junction of the center tube, which is in single-phase flow condition. Additionally, after the occurrence of boiling phenomenon in the CV120 and CV160, the magnitude of backflow rapidly increases. The Void fraction does not exist in the CV140 tubes. But in CV120, CV160 tubes, void fraction has been rapidly increased after boiling and soon been steady to a slug regime. Case 2 and case 3 total heat power is different but the void fraction of each tubes that are heated show a similar behavior unlike the case 1.

3. Conclusion

According to the complex condensation and boiling in containment building, for various reason, thermal boundary condition of multiple tube can be different. In this study, we found out that the boiling instability occurs at the case 1 situation. On the other hand, in the unequally heated situation, which maybe occurs due to screen and fouling effect, the possibility of instantaneous flow instability exists, yet eventually converges. This implies, rather in unequally heated condition, the possibility of flow instability was higher when all three tubes are equally heated.

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