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The Effects of Coolant Inventory and Noncondensible Gas on the Natural Circulation in a PWR Loop System

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PWR루프계통에서 냉각재 재고량 및 비응축성 가스의 자연순환에 미치는 영향

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Abstract

The objective of this work is to investigate the effects of diminished primary coolant inventory and the presence of noncondensible gas during single- and two-phase natural circulation in a PWR loop model. The test model was composed of two loops with a U-tube heat exchanger in each loop. Through a series of tests, it has been comfirmed that the two-phase natural circulation flow rates were greatly dependent on primary coolant inventory as previous investigators observed. The primary coolant inventory limit to maintain two-phase natural circulation was found to be the amount of the coolant necessary to keep the waterline of the coolant nozzle hole center in this model. The presence of noncondensible gas impede the single-phase natural circulation, but it did not affect the two-phase natural circulation significantly.

요 약

이 연구는 PWR를 모의한 2루프장치에서 1차냉각재의 재고량 및 비응축성가스가 單相 및 二相 자연순환에 미치는 영향을 실험적으로 조사하고져 한 것이다. 실험장치는 U 튜브를 가진 2개의 열교환기로 구성되었다. 일련의 실험을 통하여 다음 사실을 확인하였다. 二相 자연순환의 유량은 1차 냉각재 재고량의 크기에 크게 의존한다. 본 실험에서는 二相 자연순환을 유지하기 위해서는 1차냉각재 재고량의 수위가 노즐 중심선을 유지해야 함을 알게 되었다. 비응축성 가스의 존재는 단상 자연순환을 정지시킬 수 있으며 그러나 二相 자연순환에는 큰 영향을 주지 않는다.

1. Introduction

The buoyancy-driven natural circulation in the reactor coolant system of a PWR is expected to be an essential heat transfer mechanism to remove decay heat from the core during hot shutdown in the unlikely event of loss of forced circulation. Currently, three modes for the removal of decay heat from a PWR are being considered for the long-term post-accident cooling. They are single-phase natural circulation, two-phase natural circulation, and reflux condensation circulation. Especially two-phase natural circulation has been demonstrated to be an important part of decay heat removal during reactor accidents. A number of experiments have been conducted at laboratories in the United States and other countries. Through these experimental works, the major finding was that decay heat could be removed readily with the steam generator secondary side by single-phase and two-phase natural circulation, and even better by heat transfer in the reflux condensation mode. Some incidents in nuclear power plants demonstrated that natural circulation could be relied upon to cool down the plant. However, an exception can be found as in the TMI-2 accident, where the natural circulation was terminated during the accident.

It seems that possible causes of natural circulation stagnation in a PWR loop system would be the loss of inventories in both primary and secondary coolants and the presence of noncondensible gas in the primary system. The primary and secondary coolants may lose their inventory during the accident. Noncondensible gases can be introduced to the loop system with safety injection and fuel degradation during the accident. In spite of numerous experimental works that have been done, however, there were no final conclusions regarding the causes of interruption of the natural circulation in a loop system. The work should be continued to address such problems as under what conditions the natural circulation is terminated or interrupted.

The objective of this work is to obtain the qualitative experimental data that will provide additional insights into the nature of natural circulation in a PWR loop system. Special emphasis was placed on investigating the phenomenological effects of diminshed primary coolant inventory and the presence of noncondensible gas on single-phase and two-phase natural circulation in a two-loop U-tube heat exchanger model.This test facility was not designed as a prototypic model and the results should not be directly applied to a PWR. However, it is a tool to aid in understanding natural circulation in a configuration similar to a PWR.

2. Test Description

The natural circulation tests were performed in a small-scale, two-loop system which simulates the primary system of a PWR plant. When a test facility is designed to test for the understanding of the behavior of a nuclear power plant, it is important to ensure that the sizes of various components and the test conditions be properly adjusted. Since the test facility is usually reduced in size as compared with the prototype, proper scaling methodology must be used. The design of this U-tube, two-loop model was evaluated by the single/two-phase scaling ratios proposed by Ishii and Kataoka[1]. Because of practical limitations such as the size range of the commercially available U-tube heat exchanger, however, a compromise had to be made in this model design. For instance, the ID of the tubes in the model heat exchanger should be the same as that in the full-scale one. We, however, used a rather smaller size in this design.

The model was designed to be a scale factor of $\lambda = 1/5$ for length, 0.82 for hydraulic diameter, $\sigma = 1/1000$ for flow area, $\lambda\sigma = 1/5000$ for volume (except vessel volume), and $\lambda^{1/2}\sigma = 1/2236$ for core power in a full-scale PWR. Then the 15 KW core power represents a 33.5 MW decay power in a PWR roughly 1.8% of the maximum thermal power from a two-loop PWR core. This model was used under the system pressure between 0.1 MPa and 0.4 MPa. In this model, the reduced pressure scaling facility poses one problem, which is the variation of physical properties of coolant with pressure. Therefore, the simulated parameter groups can not be completely preserved. In this regard, the effect of reduced pressure scaling with fluid property group requirement expressed in Reference 2 was examined. We recognized that there are some difficulties in either preserving the power level or time scale. Nevertheless, the reduced pressure scaling offers an advantage due to its low experimental cost.

The test loop system consists of three basic components including a steel vessel which accommodates an electric heater unit, two heat exchangers or steam generators through which secondary cooling water is provided, and an expansion tank which allows for the specific volume changes of the water during heatup and cooldown. The pipes that connect the vessel to the heat exchangers are identified as hot legs and cold legs. An isometric view of test loop system is shown in Figure 1.

The vessel is a steel cylinder of 320 mm ID, 940 mm height and 4 mm wall thickness designed for 0.5 MPa at 151°C. The electric heater installed in the vessel is a six-element immersion type heater. The electric capacity of each element is 5 KW and the maximum capacity is 30 KW with six elements active. The heat exchanger is a U-tube, recirculation type as shown in figure 2. Each heat exchanger has U-tubes. The tube outer and inner diameters are 15.2 mm and 13.2 mm, respectively. Each lower tube header splits two portions by a partition wall. One portion of the tube header is connected to the hot leg and the other portion is connected to the cold leg. Each hot leg, consisting of 35 mm ID copper pipe, connects the upper outlet from the vessel to the lower tube header of the heat exchanger. Each cold leg, of the same material and size as the hot leg, connects the outlet of the heat exchanger to the bottom of the vessel. The vessel and piping were insulated by 3.0 cm premolded fiberglass. Hot water from the vessel flows to 8 U-tubes in each heat exchanger through the hot leg and returns to the bottom of the vessel through the cold leg after cooling down by secondary coolant flow.

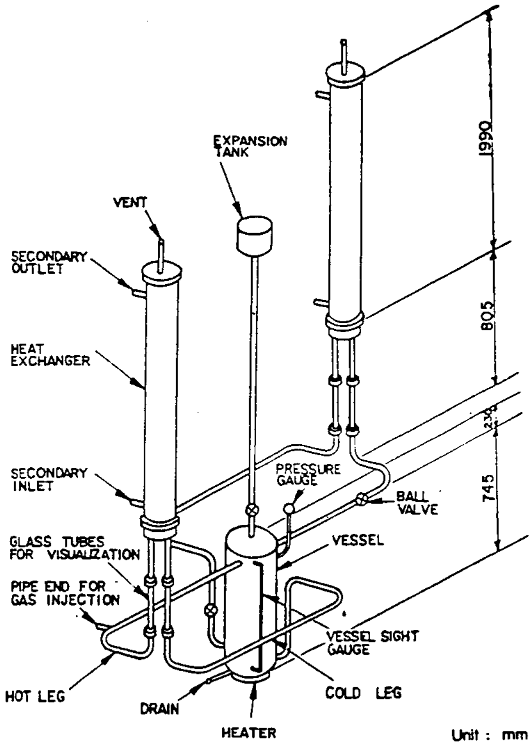

Fig. 1. Isometric View of Test Loop Facility

Two transparent pyrex glass tubes were installed at the vertical section of each hot and cold leg to measure the flow rate of primary coolant by means of tracing dye movement method. A tube for injecting a noncondensible gas into the system is connected to the lower section of each

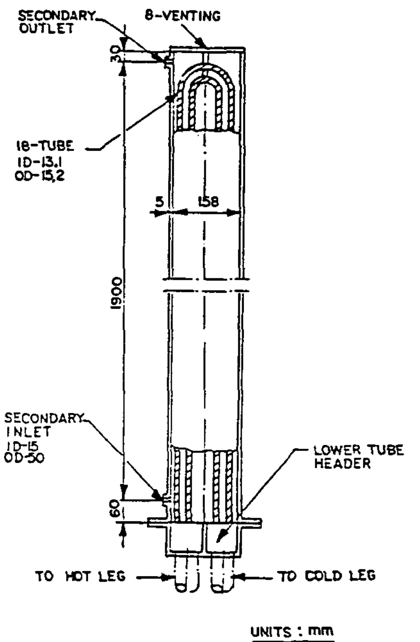

Fig. 2. U-Tube, Recirculation Type Heat Exchanger

hot leg. The two loops are made geometrically symmetric, and we designated the two loops of the models as left and right loops. Each loop can be isolated by the valves at hot and cold legs of the left loop. Some critical parameters of the model are listed in Table 1. As a noncondensible gas, nitrogen gas was injected into the hot leg using an injection system during the test run. A total of 12 Type K thermocouples were installed in the facility; two of those were in the vessel, six were in the primary system, and four were in the secondary system. To measure the primary system pressure variation during the test, one absolute pressure transducer was installed in the upper head of the vessel. Signals from the thermocouples and pressure transducer were received and processed by HP 9825A data acquisition system every one minute.

The velocities of injected fluorescent dye movement with the primary coolant flow were measured by a stop watch visually at the transparent sections of each hot and cold leg. For higher flow velocity regime, the movie camera technique was applied to measure the flow velocity with fluorescent dye injection. The hot leg section was used for the single-phase flow, and the cold leg section was used for the two-phase flow. The secondary flow rates were controlled by valves at each upstream of coolant inlets, and measured by rotameters installed at each inlet of secondary flow. The flow rates of noncondensible gas were measured by a gas rotameter. Electric power to the heater was measured by an AC wattmeter. The core power was varied between 5 and 30 KW, which represents approximately 0.6 to 3.6% of the full core power. Experimental errors involved in the measurements were estimated at $\pm 0.5°C$ for temperature, ± 3 kPa for pressure, $\pm 2\%$ for the flow rate in the rotameter, and $\pm 5\%$ for the primary flow rate.

As a general procedure, prior to start every test, all the vents were opened and the system was filled with demineralized water. Valves at the top of all U-tubes in each heat exchanger served for venting the trapped air in the system. When it was full, the water was turned off and the vents closed. Meanwhile the data acquisition system was turned on and put into automatic mode for taking data on temperatures and pressure in the system during the test run. The system was heated using the core power as a heat source and the heat exchanger was cooled by the secondary coolant as a heat sink. The core power and secondary flow rate were set to the appropriate settings for the test. Once the steady-state was reached for each run, measurement of primary flow rate of natural circulation was then taken by injected dye movement. Primary coolant inventory was controlled by draining the fluid from the bottom of the vessel with the vents opened at the top of the U-tubes. The water level gauge

Table 1. Test Parameters for Two-Loop Model

Number of Loops	2
Maximum Core Power (KW)	30
Maximum Design Pressure (MPa)	0.5
Total Primary Volume (litre)	
For Single-Loop	77
For Two-Loop	88
Vessel	
Material	Steel
Height (mm)	940
Inside Diameter (mm)	320
Legs	
Material	Copper
Inside Diameter (mm)	35
Heat Exchanger	
Type	U-Tube, Recirculation
Number of Tubes	8
Tube Material	Copper
Inside Diameter of Tube (mm)	13.1
Average Length of Tube (m)	3.90
Heat Transfer Area (m^2)	1.47
Inside Diameter of Shell (mm)	158

Table 2. Range of Test Variables for Two-Loop Test

Test Type	Primary Inventory (% of total)	Core Power (KW)	Secondary Flow Rate (Kg/s)	Amount of Noncondensible gas (litre)
Single-Phase				
Single-loop	100	5 to 15	0 to 0.028	—
Two-loop	100	5 to 15	0.028	—
Two-Phase				
Single-loop	93 to 62	15 to 25	0.014~0.028	—
Two-loop	—	—	—	—
Effect of Noncondensible Gas				
Single-phase	≈ 100	10	0.028	up to 4.0
Two-phase	85	20	0.014	3.0

was installed at the vessel. Table 2 summarizes the range of the test variables encountered for the various tests.

3. Experimental Results and Discussions

Presented first are the general aspects of each mode of natural circulation. Next, the test results of the effect of diminished primary coolant inventory on natural circualtion is provided. Finally, a description of the effect of noncondensible gas during both single-phase and two-phase natural circulation is presented.

3.1 General Asepcts of Single-Phase and Two-Phase Natural Circulation

The driving mechanism in single-phase natural circulation is an overall loop liquid density difference caused by temperature difference. The temperature difference between hot and cold legs generally depends on the core power, secondary cooling condition, and number of active loops. Figure 3 shows the test results of the primary flow rates, i.e., natural circulation rates, as a function of core power with full primary inventory and fixed secondary flow rate (0.028 kg/s) during

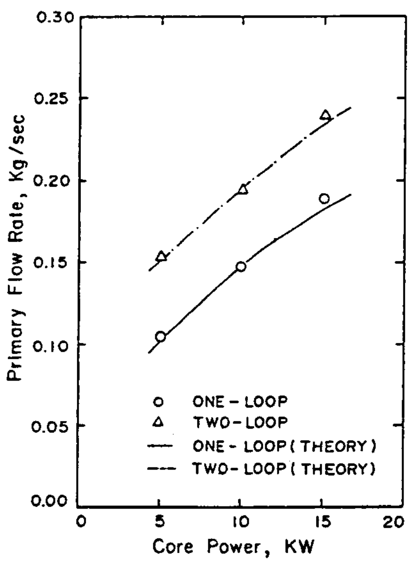

Fig. 3. Primary Flow Rate as a Function of Core Power, Single-Phase

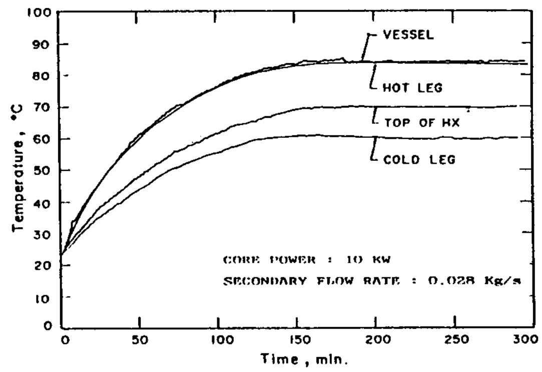

Fig. 4. Temperature Histories, Sigle-Phase

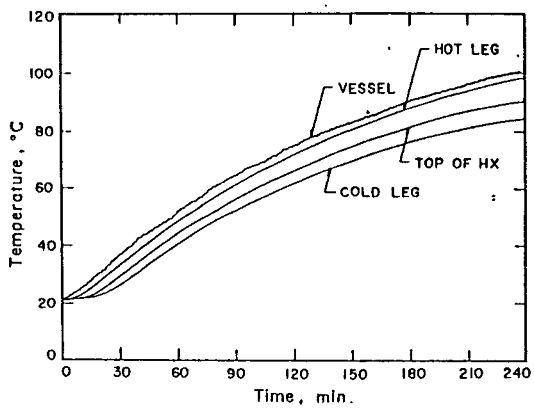

Fig. 5. Temperature Histories, Sigle-Phase, Core Power: 10 KW, No Secondary Flow

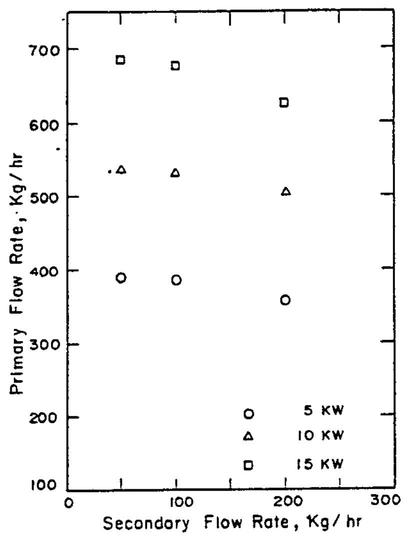

Fig. 6. Effect of secondary Flow Rate on Primary Flow Rate, Single-Phase

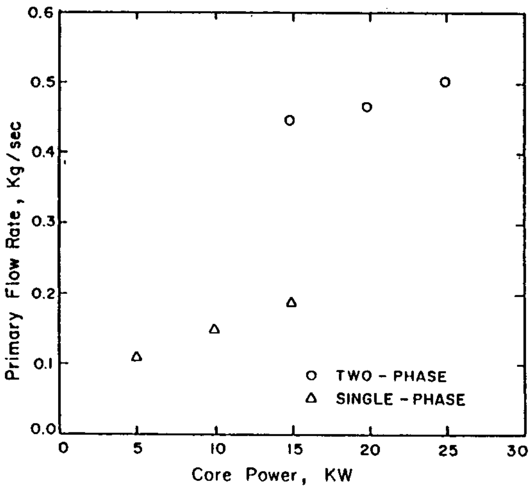

Fig. 7. Primary Flow Rate as a Function of Core Power, Secondary Flow Rate: 0.014 kg/s

single-loop and two-loop operations. In this figure, the measured values of the primary flow rates were compared with the calculations based on conventional formulations for single-phase, one-dimensional natural circulation in the fluid loop[3].

For the calculation of the primary flow rate, the height difference of 1.55 m between the hot and cold fluid and the turbulent flow resistnace of $23 \times 10^{6} m^{-4}$ for one loop were employed. We obtained the turbulent flow resistance from the pressure drop measurements in the model. Figure 4 shows the typical individual test result for temperature variations with time during single-phase natural circulation. The test conditions were 10 KW core power, 0.028 kg/s secondary flow rate, and two loops active. It can be seen that the equilibrium state was reached at about 170 minutes after test initiation. In case of zero secondary flow rate, the equilibrium state could not be established whithin the test duration as shown in Figure 5.

it was found that there was an influence of secondary flow rate on the primary flow at fixed core power as shown in Figure 6. Higher secondary flow rates caused lower temperature differences between the hot and cold lengs because of the higher cooling effect. This resulted in the lower primary flow rate.

The general characteristic of two-phase natural circulation is the presence of saturated steam bubbles in the core, hot leg and heat exchanger inlet. As a direct result of the presence of steam bubbles in the hot side of the loop system, the primary coolant flow rates for the two-phase regime are generally higher than those for single-phase because the overall density gradient between the hot and cold sides of the heat exchanger is higher. Figure 7 indicates the primary flow rates during two-phase natural circulation as a function of core power with constant secondary flow rate (0.014 kg/s). It should be noted that two-phase natural circulation was usually established when some of the primary coolant was drained. Thus, the above tests for two-phase natural circulation were performed with 85% primary inventory. Figure 8 shows a sample of temperature histories during the test for two-phase natural circulation with secondary cooling.

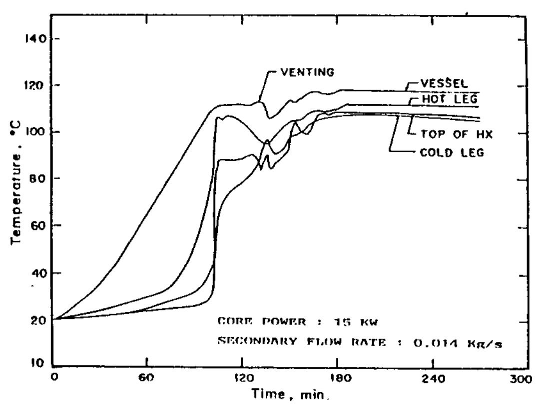

Fig. 8. Temperature Histories during Two-Phase Natural Circulation

3.2 Effect of Primary Coolant Inventory on Two-Phase Natural Circulation

To investigate the effect of diminished primary coolant inventory on natural circulation, a total of 15 tests were performed during two-phase natural circulation with the inventory range between 93 and 62 percent of the total coolant volume. Figure 9 presents the test data of the primary coolant flow rate at the cold leg side as a function of primary coolant inventory for three core power cases. All of these tests were run in the single loop, and the secondary flow rate was kept at 0.028 kg/s. At each test, the equilibrium state was established at about 90 minutes after test initiation. As can be seen in this figure, the trend for the three power cases is similar with that of the highest primary flow rate during two-phase natural circulation occurring at about 85% inventory. It was also found that the two-phase flow was completely terminated at 62% inventory. The 62% inventory was identified as the coolant volume in the vessel just of the level of coolant nozzle hole center.

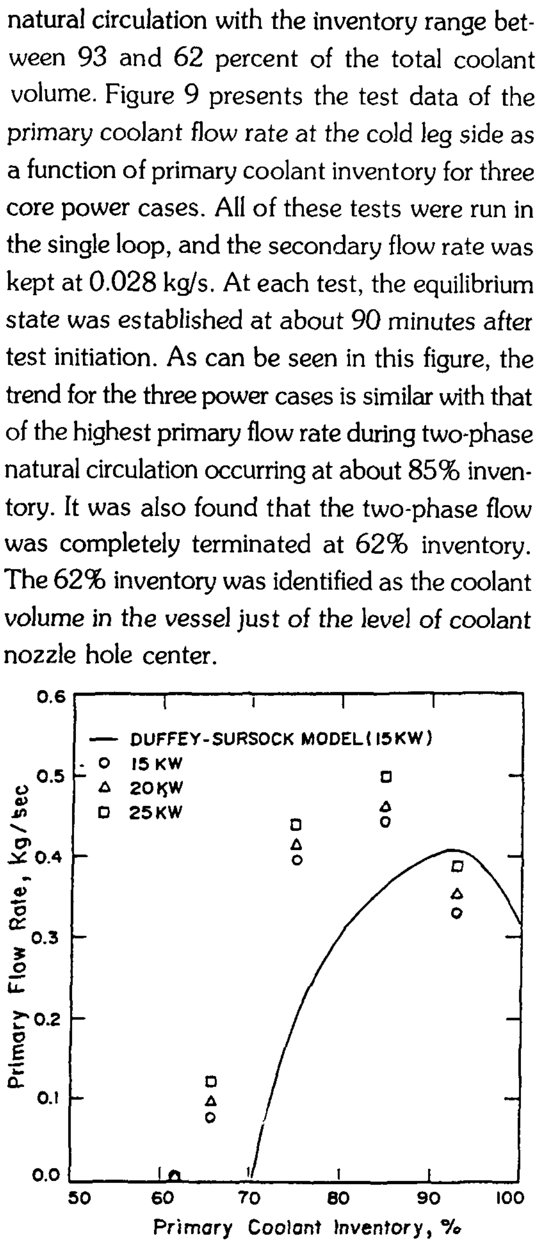

Fig. 9. Primary Flow Rate as a Function of Primary Coolant Inventory During Two-Phase Natural Circulation

Single-phase natural circulation generally occurs only at about 100% primary inventory. Starting with single-phase natural circulation, draining the primary coolant from the system produced saturated conditions and two-phase flow commenced. As draining progressed, the primary coolant flow rate gradually increased and peaked at around 85% inventory. it seems that the increase in primary flow rate is mainly attributed to increase in the fluid density difference between hot side and cold side. As more fluid was drained, void was also increased, and eventually void extended over into the heat exchanger downflow side. Then an abrupt reduction in primary flow rate was caused due to the reduction of the overall driving head. When the primary coolant inventory was decreased below 62% inventory, the heat exchanger tubes, the hot leg, and the upper part of the vessel were almost voided of liquid, and the two-phase natural circulation was discontinued. This means the complete loss of the driving head of the two-phase natural circulation. Thereafter, the reflux condensation circulation will be commenced. A similar trend was observed at INEL[4]. The experimental data trend on the effect of primary coolant inventory has been compared to the Duffey-Sursock model[5] with proper estimation of flow loss coefficient as shown in Figure 9.

3.3 Effect of Noncondensible Gas Injection on Single- and Two-Phase Natural Circulation Modes

With regard to the effect on thermal-hydraulic response due to the presence of noncondensible gas in the primary loop during natural circulation, report of work performed at SRI[6] indicates that the noncondensible gas could impede the single-phase natural circulation, but a later report[7] described that there is no effect of noncondensible gas on single-phase natural circulation. Reports of work at SRI[8] and INEL[4] show that the introduction of noncondensible gas into the primary side resulted in the increase of the primary system pressure and temperatures, but there was no mention about the interruption of natural circulation. Report of work done previously at KAERI[9] indicates that the presence of nitorgen gas in the primary system could greatly impede the natural circulation, even in two-phase natural circulation. But they had a different structure of the heat exchanger, i.e., the shell and tube type. At present, no definite conclusion can be made as to the effect of noncondensible gas on natural circulation.

To discover the effect of noncondensible gas on system thermal-hydraulic response during single- and two-phase natural circulation with the U-tube heat exchanger, various amounts of nitrogen gas were introduced at the hot leg of the loop. Various tests for single-phase natural circulation with noncondensible gas injection were performed for four different operating configurations. The variable parameters for these tests were the number of active loops, the number of gas injected loops, and the secondary cooling conditions.

Figure 10 shows how typically the noncondensible gas injection affected single-phase natural circulation. This figure presents a complete set of the graphical results for the first operating configuration, i.e., single loop active with the secondary coolant flow. The test conditions were 10 KW core power and 0.028 kg/s secondary coolant flow rate. Shown in Figure 10 are the variations of temperatures in the system, the system pressure and the primary flow rates as a function of time with the several nitrogen injections indicated on the plots. The amount of each nitrogen injection was 0.2 litre at preinjection system pressure and temperature. The first nitrogen injection produced increase of

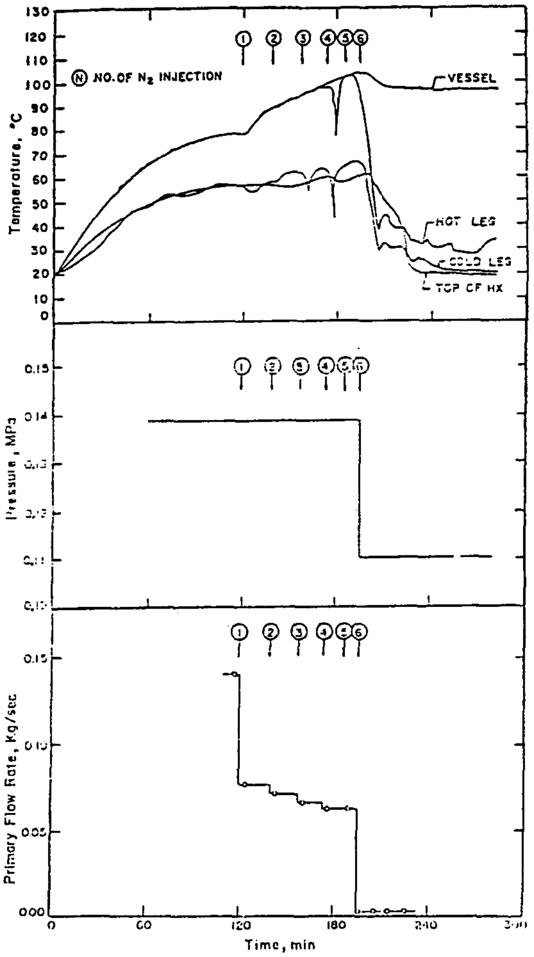

Fig. 10. Effect of Noncondensible Gas on Single-Phase Natural Circulation, Single Loop Active, Single Side Injection, Core Power: 10 KW, Secondary Flow Rate: 0.028 kg/s

temperature at the vessel and hot leg, and a significant decrease of primary coolant flow rate. The second and third injections resulted in further increase in temperature in the system and slight reduction of primary flow rate. After the fourth injection, it was found that a dramatic drop in temperature was observed at the hot and cold legs. It seems that the temperature drop and the decrease of the primary flow rate were caused by an increase in hydraulic resistance due to the presence of nitrogen gas in the primary system. We postulate that under this circumstance, most of the nitrogen gas is congregated in the upper part of the U-tubes. After the sixth injection, the primary flow was completely stagnated and the system pressure dropped from 0.14 to about 0.11 Mpa. The system pressure of 0.14 MPa simply represented the hydrostatic head of the coolant in the loop system. Dropping to 0.11

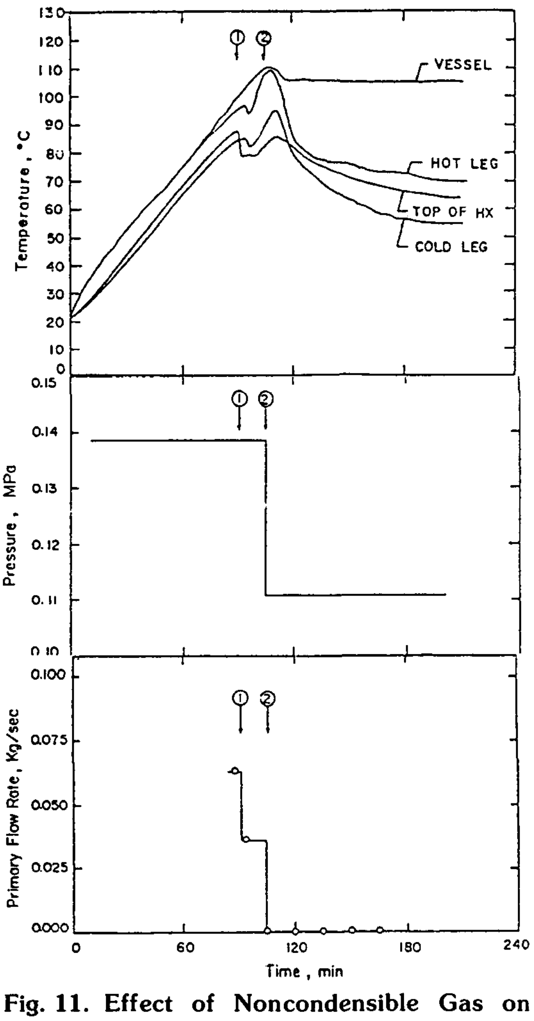

Fig. 11. Effect of Noncondensible Gas on Single-Phase Natural Circulation, Single Loop Active, Single Side Injection, Core Power: 10 KW, No Secondary Flow

MPa means that a considerable volume of void was formed in the upper part of the heat exchanger by the nitorgen gas. It appears that a total of 1.2 litres of nitorgen gas (1.56% of the system volume) was enough to completely block the tube flow during single-phase natural circulation. The tube blockage behaved like a plug of nitrogen gas at the top of U-tubes. As a result of the cessation of natural circulation, the temperatures at the hot leg, top of heat exchanger tubes, and cold leg in the active loop side decreased abruptly.

Figure 11 presents the test data for the second operating configuration, i.e., the case of single loop active without secondary coolant flow. This test was carried out with 10 KW core power. During the test, the two nitrogen injections were performed. The volume of each nitrogen gas injection was 0.2 litre. Because of zero secondary flow, the temperature difference between the hot and cold sides was smaller than the first case. Therefore it caused the lower primary flow rate. The first injection produced an increase of temperatures in the system and a significant decrease of the primary flow rate. After 15 minutes of the first injection, the second injection was made. Then the loop flow was completely stagnated. It appears that the smaller amount of injected nitorgen gas had easily blocked all the tubes because the momentum of primary flow was somewhat weak.

Shown in Figure 12 are the thermal-hydraulic responses in the right side loop with two loops active and single side injection with secondary coolant flow. The test conditions were 10 KW core power and 0.028 kg/s secondary flow rate. A total of 4 litres (4.5% of system volume) was injected in the right side loop. As can be seen, the first injection produced a substantial decrease of primary flow rate and a gradual temperature increase in the vessel. After the seventh injection, some fluctuation of temperatures at the hot and cold legs appeared, but there was no primary flow stagnation during the period of test.

Figure 13 shows the test for the fourth operating configuation, i.e., two loops active and two sides gas injection with secondary coolant flow. The test was performed with 10 KW core power and 0.028 kg/s secondary flow rate. The nitogren gases were injected in both cold and hot legs simultaneously during single-phase natural circulation. The volume of nitorgen gas of each injection was 0.2 litre. After the fourth injection, the simultaneous stagnation of primary flows in both loops was observed.

To observe the effect of noncondensible gas injection during two-phase natural circulation, some amount of nitrogen gas was also injected into the hot leg during single-loop operation. The principal effects of noncondensible gas injection on thermal-hydraulic response were to increase the pressure and temperatures in the system with an increase in the volume of the injected gas. But there was no primary flow stagnation during the

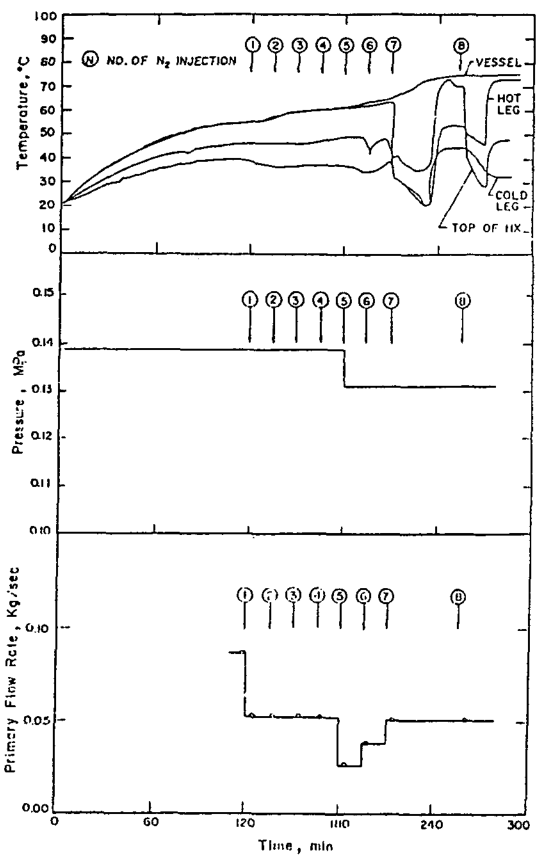

Fig. 12. Effect of Noncondensible Gas on Single-Phase Natural Circulation, Two Loops Active, Single Side Injection, Core Power: 10 KW, Secondary Flow Rate: 0.028 kg/s

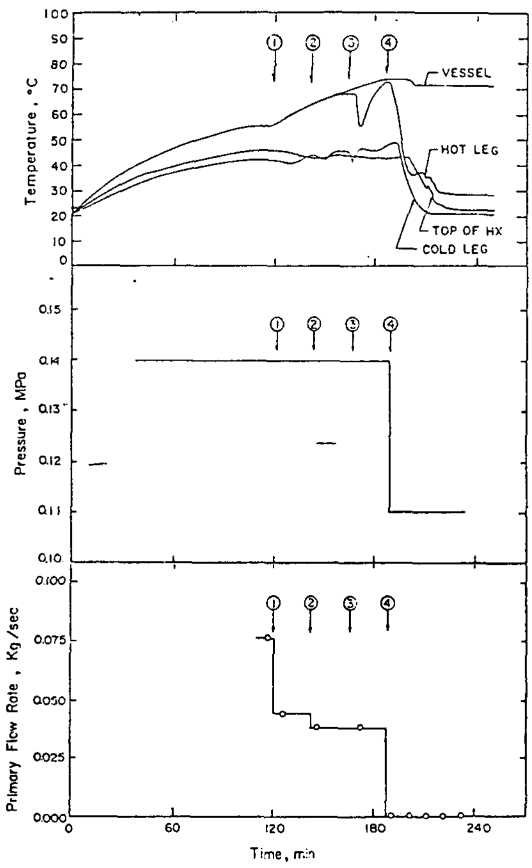

Fig. 13. Effect of Noncondensible Gas on Single-Phase Natural Circulation, Two Loops Active, Two Sides Injection, Core Power: 10 KW, Secondary Flow Rate: 0.028 kg/s

period of test. The test was performed under conditions of 20 KW core power and 0.028 kg/s of secondary flow rate. The amount of each nitorgen gas injection was 0.5 litre at the corresponding pressure and temperature. Figure 14 hows a set of test results for two-phase natural circulation with a series of nitorgen gas injection. Only the right side loop was active. Top of the figure represents the temperature histories in the vessel, in the hot leg, at the top of the heat exchanger and in the cold leg with nitrogen gas injections. The gradual increase of temperature

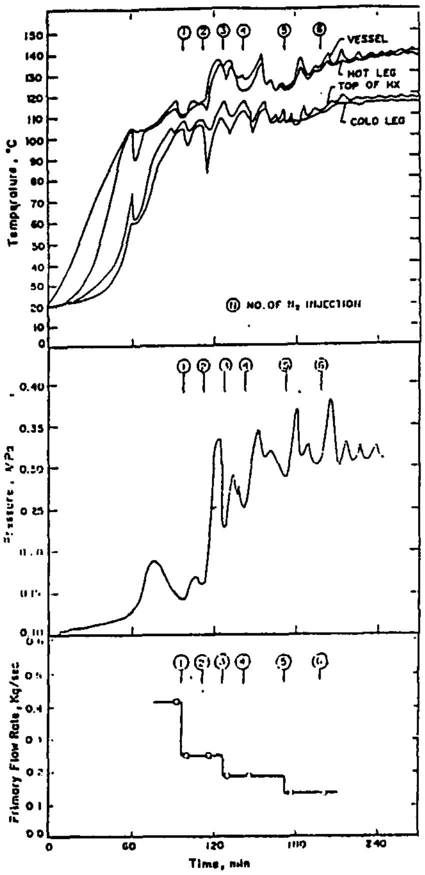

Fig. 14. Effect of Noncondensible Gas on Two-Phase Natural Circulation, Single Loop Active, Single Side Injection, Core Power: 20 KW, Secondary Flow Rate: 0.028 kg/s

with increasing amount of the injected nitorgen gas could be observed. There were significant fluctuations or oscillations of temperatures during the test. Should the amount of nitrogen gas increase to occupy the volume in the U-tube, some of the loss of the heat sink would simply raise the system pressure. We observed a slight decrease of primary flow rate after the first injection, but there was no primary flow blockage during the test. The decrease in the primary flow was attributed to an increase in hydraulic resistance caused by the presence of nitrogen gas in the heat exchanger. But it was not enough to interrupt the flow. It appears that the higher velocity of two-phase flow had enough momentum to break through the congregated nitorgen gas in the upper part of the U-tubes. The trend of the above test was also similar to that of the work at INEL[4]. As we slightly mentioned in the earlier part of this section, the stagnation of two-phase natural circulation due to the noncondensible gas injection was observed in the work at KAERI[9]. There the shell and tube type heat exchanger was used instead of the U-tube type. Judging from this, there is an influence of geometric structure of the heat exchanger on the thermal-hydraulic response due to the noncondensible gas injection during two-phase natural circulation.

The results on the natural circulation presented herein can be used for validation of the current thermal hydraulic system computer codes for accident analysis.

4. Conclusions

A series of tests were performed in the U-tube two-loop model with the objective of further understanding single- and two-phase natural circulation. Special emphasis was placed on investigating the effects on natural circulation of diminished primary coolant inventory and the presence of noncondensible gas in the primary system. The principal results of the tests are:

1. Steady-state single and two-phase modes of natural circulation were established in the single-loop and two-loop configurations, and the general aspects of these modes were observed. It was observed that the natural circulation in a PWR-type loop system is an effective mechanism for removal of core decay heat to the secondary side over a core decay power range of 0.6 to 3.6%.

2. With regard to the effect of diminished primary coolant inventory on two-phase natural circulation, the overall primary flow rate was found to vary depending on the primary inventory. As the primary coolant inventory was decreased below the level of the coolant nozzle hole center, the heat exchanger tubes, the hot leg, and the upper part of the vessel were almost voided of liquid, and the complete loss of the driving head of two-phase natural circulation occured.

3. During single-phase natural circulation with the U-tube heat exchanger, introduction of a certain amount of noncondensible gas in the primary may impede the primary flow. This may disrupt the core decay heat removal capability of the steam generator. During two-phase natural circulation, however, it did not stagnate the primary flow in the present work.

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