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An Investigation of Fluid Mixing with Direct Vessel Injection

Jong Hee Cha and Hyung Gil Jun
Korea Atomic Energy Research Institute
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직접용기주입에 따른 유체혼합에 관한 연구

차종희 · 전형길
한국원자력연구소
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Abstract

The objective of this work is to investigate fluid mixing phenomena related to pressurized thermal shock(PTS) in a pressurized water reactor(PWR) vessel downcomer during transient cooldown with direct vessel injection(DVI) using test models. The test model designs were based on ABB Combustion Engineering(C-E) System 80+ reactor geometry. A cold leg small break loss-of-coolant accident(LOCA) and a main steam line break were selected as the potential PTS events for the C-E System 80+. This work consists of two parts. The first part provides the visualization tests of the fluid mixing between DVI fluid and existing coolant in the downcomer region, and the second part is to compare the results of thermal mixing tests with DVI in the other test model. Flow visualization tests with DVI have clarified the physical interaction between DVI fluid and primary coolant during transient cooldown. A significant temperature drop was observed in the downcomer during the tests of a small break LOCA. Measured transient temperature profiles agree well with the predictions by the REMIX code for a small break LOCA and with the calculations by the COMMIX-1B code for a steam line break event.

요 약

이 연구는 가압경수로의 원자로 다운커머내에서 과도냉각시 직접용기주입에 따른 유체혼합현상을 가압열충격의 견지에서 시험모델을 사용하여 조사한 것이다. 시험모델은 ABB-CE System80+ 원자로 구조에 근거하여 설계되었다. 이 원자로에 대한 가능성 있는 가압열충격 사고로서 콜드레그 소형파단 냉각재 상실사고와 주 증기관 파단 사고가 선정되었다. 시험은 두 부분으로 구성되는데 첫째 부분은 원자로 다운커머에서 직접용기 주입수와 기존냉각재간의 유체혼합을 가시화법에 의하여 시험한 것이고, 둘째 부분은 별도의 시험모델에서 직접용기주입에 따른 열적혼합을 시험한 것이다. 가시화 시험에서는 과도적 냉각기간중 직접용기 주입수와 1차 냉각재간의 물리적 상호작용이 밝혀졌다. 열적혼합시험에서는 소형파단 냉각재 상실사고시 직접용기주입에 의한 심한 냉각현상이 다운커머내서 관찰되었다. 측정된 온도곡선은 소형파단 냉각재 상실사고에 대하여 REMIX 코드, 증기관 파단사고에 대하여는 COMMIX-1B 코드에 의한 계산과 비교되었다.

1. Introduction

Under certain postulated accident conditions such as small break loss-of-coolant accident(LOCA), main steam line break, feed water pipe break and other overcooling scenarios, the reactor vessels of pressurized water reactors(PWRs) undergo a large cooling rate while retaining significantly high internal pressures. Under these circumstances, the injection of cold water induces a themal stress at the inside surface of the reactor vessel, and this thermal stress can be compounded by pressure stresses. Such pressurized thermal shock(PTS) events might enhance the propagation of pre-existing flaws and cause through-wall cracking of radiation embrittled reactor vessels. Because the coolant water in the vessel warms the injected water, the cooling rate at the vessel wall depends on the thermal mixing conditions in the downcomer.

According to the Electric Power Research Institute (EPRI) Advanced Light Water Reactor(ALWR) Utility Requirements Document, the safety injection system in a PWR shall be discharged directly into the reactor vessel downcomer annulus rather than into the cold legs. Use of this direct vessel injection(DVI) rather than cold leg injection would allow a reduction in safety injection pump capacity requirements for the cold leg break as well as a reduction of safety injection tank volume. In accordance with the EPRI ALWR Requirements, the emergency core cooling system in the ABB Combustion Engineering (C-E) System 80+[1] employs four trains of high pressure safety injection pumps and safety injection tanks which inject the water directly into the vessel annulus in stead of cold leg injection.

The objective of this work is to investigate fluid and thermal mixing phenomena in situations producing the pressurized thermal shock in the downcomer of a PWR during a cooldown transient caused by direct vessel injection. This work consists of two parts. The first part provides flow visualization of the early part of the transient and detailed flow field information during the safety injection in the downcomer area of the test model. The second part contains thermal mixing data between injected cold water and hot existing coolant in the downcomer during cooldown transient. The experimental thermal mixing data were compared with the predictions by the computer codes. The test models were designed to simulate the reactor vessel of ABB Combustion Engineering System 80+.

Seveval previous experimental studies dealing with PTS and fluid and thermal mixing in the reactor vessel have been reported over the last decade. Fluid mixing experiments in a facility with a 1/2-scale transparent model of a typical PWR cold leg, downcomer, and lower plenum were performed by Theofanous[2]. It was found that the fluid mixing data were in good agreement with the detailed predications of the Regional Mixing Model. Visualization tests of fluid mixing were performed by Valenzuela and Rothe[3] in a 1/5 scale model of a PWR cold leg and downcomer which have a horizontal cold leg. These results helped to clarify the detailed mixing phenomena that were relevant to the thermal-hydraulic aspects of PTS. Rothe et al. [4, 5] have investigated the thermal mixing and vessel wall heat transfer in the cold leg and downcomer with a 1/2-scale test facility of a PWR during a cooldown transient caused by the injection of cold water in a stagnant loop. The overall response of the facility during a simulated overcooling transient exhibited almost perfect thermal mixing. The above investigations concern mostly cold leg injection. There is no report on the fluid and thermal mixing studies relating to the direct vessel injection.

2. Test Description

2.1. Flow Visualization Tests

The flow visualization tests were performed in a 1/5-scale transparent model of the downcomer of a PWR. Major linear dimensions of the test model were reduced from values typical of prototype C-E System 80+ by a factor of approximately five. The scaling of the test model was selected in order to facilitate observation of the mixing phenomena of DVI water in the downcomer annulus of a PWR under conditions important to pressurized thermal shock. In order to maintain the geometric and dynamic similarities of the test model, all ratios of flow path physical dimensions and Froude numbers were preserved. Froude number, Fr, ratio of inertial to bouyant forces in a fluid stream, is defined as:

$$Fr = \frac{v}{\left[g D (\rho_{DVI} - \rho_b)/\rho_b \right]^{1/2}} \tag{1}$$

where v=DVI fluid velocity(in m/s), g=acceleration of gravity(in m/s^2), D=diameter of DVI line(in m), ρ_{DVI} =density of DVI fluid(in kg/m^3), and ρ_b=density of bulk fluid.

The test model represented a 90° planar section of a reactor vessel downcomer and lower plenum based on prototype geometry. The basic downcomer geometry is shown in Figure 1. This model includes only one DVI nozzle. The diameter of DVI nozzle is 43mm, and the width of the model is 645mm. The height in the downcomer above the DVI nozzle centerline is 294mm, and the gap in the downcomer is 50mm, which was the minimum width that the wall surface effect was negligible. The total height of the model is 2112mm. The test model was fabricated from transparent acrylic plate having a nominal thickness of 10mm.

As result of system analysis at ABB Combustion Egnineering[6], a 0.05ft^2 cold leg small break LOCA at full power and a double-ended break of main steam line at zero power with a concurrent loss of offsite power were selected as the representative PTS envents. In a small break LOCA, the reactor coolant system depressurizes fairly rapidly until the safety injection starts and then repressurizes to near the shutoff of the safety injection pumps. The system pressure is retained high for a long period. The cold safety injection water is injected into the downcomer. The coolant in the reactor vessel downcomer annulus remains about 1.5m above the top of the core. In the case of a steam line break, the reactor coolant system rapidly depressurizes as the result of the blowdown of the ruptured steam generator to atmospheric pressure until the safety injection starts, and then the system repressurizes to near the shutoff head of the safety injection pump. The cold safety injection water enters the downcomer region. The reactor downcomer annulus remains full of liquid. In this case, some loop flow in the cold leg caused by natural circulation with the ruptured steam generator may by assumed. But in these visualization tests,

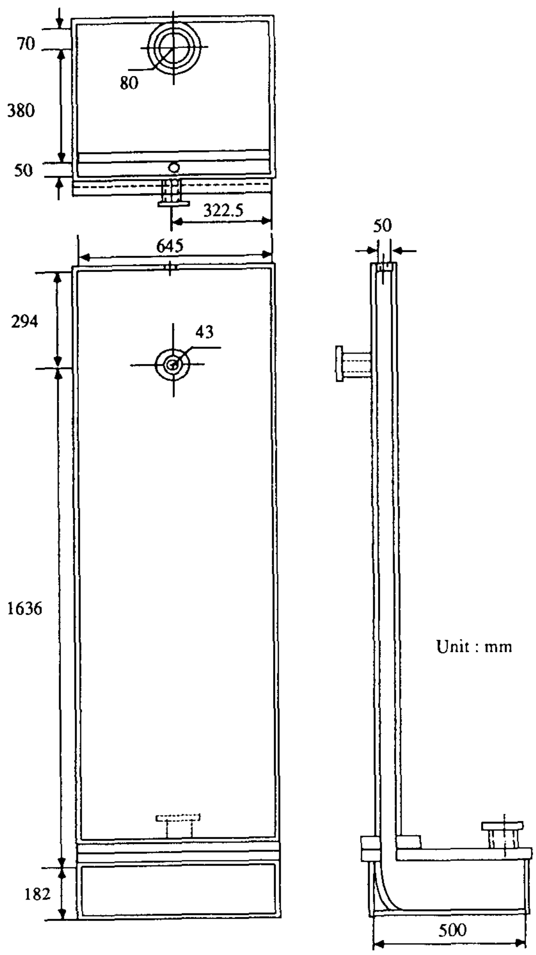

Fig. 1. Flow Visualization Test Model

such loop flow was not taken into account for simplification of the test. Based on the results of above analyses, two separate test conditions of the coolant levels in the downcomer annulus were selected. One is that the level in the downcomer is equal to the cold leg coolant level, and the other is that the downcomer annulus is full of coolant with stagnant loop flow. The coolant levels were adjusted by controlling the height of overflow from a standpipe which was connected verically to the top of lower plenum.

Safety injection flow rate depends on the performance of safety injection pump. Safety injection flow rates can be determined from this safety injection pump performance information and the scenario of the event. The Froude number is a function of the liquid density at the safety injection nozzle. In order to preserve the DVI Froude number during the tests, the density of safety injection water was adjusted by adding salt. The range of DVI Froude number was chosen to be 0.81 − 3.20. During the visualization tests, the concentration of salt was kept at 4.4%. The test conditions for the visualization test are summarized in Table 1. All flow visualization tests described here were performed by the dye injection method. The dye(red color) was added to the DVI water storage tank, and therefore the DVI flow was dyed throughout the tests. The motion of the dye fluid was recorded by video recorder at speed of 250 frames per second.

The first step of the test is to prepare the injection water in the 400 litre storage tank with dye and salt. The second step involves filling fresh water into the test model to be used from the tap water line. During this process, the vent located at a high point in the test model was opened to discharge air in order to completely fill the test model with water. The video camera was installed in front of the test facility. After all pre-test checks were completed, the DVI flow rate was adjusted to meet the specified Froude number for the test to be performed. The selected flow rate was adjusted using the flow meter in a bypass loop that could be isolated from the test model with a quick-acting three-way valve. At the same time, the video camera was turned on the take a moving picture. A test was initiated by opening the valve for DVI injection while simultaneously closing the bypass loop.

2.2. Thermal Mixing Tests

The thermal mixing tests were carried out in a 1/5-scale model simulating configurations of ABB C-E System 80+ reactor vessel. This model was designed to represent the whole 360° section of the vessel except for the upper plenum part. The model includes four safety injection nozzles, two hot leg outlet nozzles and four cold leg inlet nozzles. The inside diameters of the DVI nozzle, the cold leg nozzle, and the hot leg nozzle were 42mm, 150mm, and 200mm, respectively. The gap in the downcomer was 46mm. The inside diameter of the vessel was 824mm, and the total height of the model was 2334mm. All ratios of flow and path dimensions and all angles of test model are the same as in the prototype. The test model was fabricated from carbon steel plate having a nominal thickness of 5mm. Figure .2 shows the basic geometry of the 1/5-scale themal mixing test model, and Figure 3 shows the location of thermocouples in the thermal test model.

As shown in Figure 4, which shows a schematic diagram of the test facility, the test facility includes two water storage tanks. One is for DVI water, and other one is for loop flow water. The capacity of each tank is 600 litres. Water was supplied to the test model through a rotameter by a centrifugal pump. Two assemblies of immersion type electric heaters, 25kW capacity each, were installed in the bottom of the test vessel and in the loop flow water storage tank for adjustment of water temperatures. System measurements consisted of flow rates and temperatures of the DVI injection and the loop flow in the facility. These measurements were used to establish and control the operating conditions of the facility. Flow temperatures in the test model were measured at eight locations in the downcomer region including three points in the active core region. Test data were recorded from all instruments simultaneously on a computer-based data acquisition system.

As with the flow visualization tests, the thermal mixing tests were performed under two conditions. One was tnat the downcomer water level equal to the cold leg level of coolant without loop flow, thus simulating a small break LOCA; and the other was that the downcomer was full of coolant with loop flow, thus simulating a steam line break. For the tests of the former case, safety injection water only was drawn from the storage tank; and for the tests of the latter case, both the DVI water and the loop flow water were supplied simultaneously to the test model from the storage tanks. The coolant levels were adjusted by shifting of the hot leg outlet extension. During the tests, DVI Froude number was preserved with the prototype. The initial temperatures of DVI injection and coolant in the downcomer were 10°C and 94°C, respectively. The temperature of loop flow water in the storage tank was kept at 94°C. The tests were conducted with DVI injection flows and loop

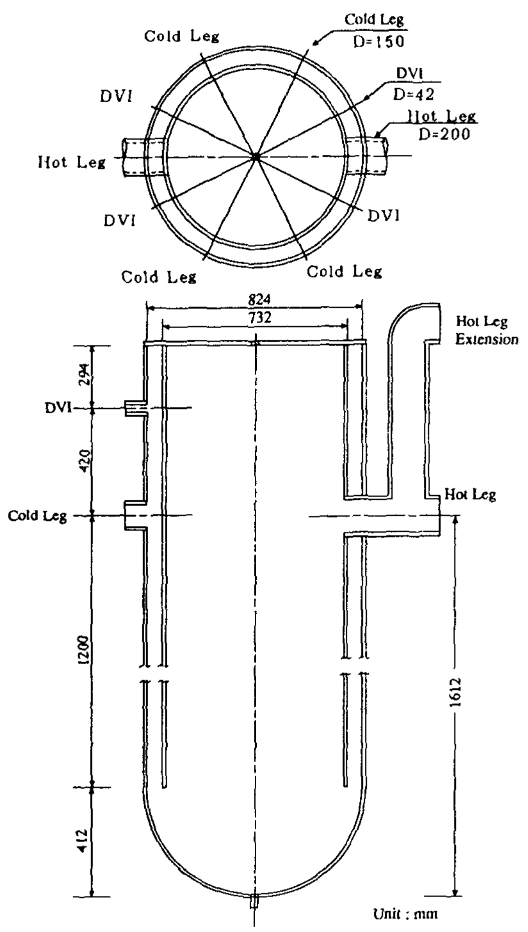

Fig. 2. Thermal Mixing Test Model

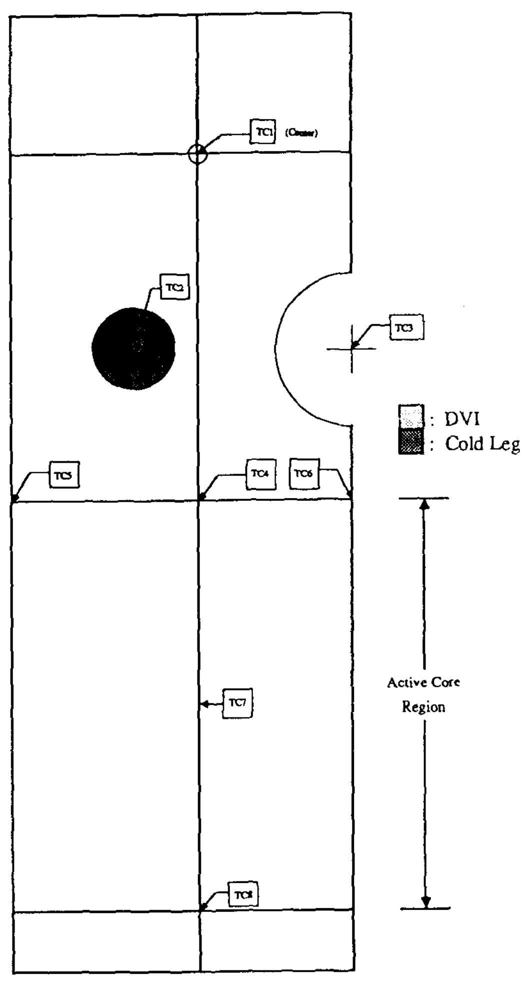

Fig. 3. Location of Thermocouples in 1/4 Sector

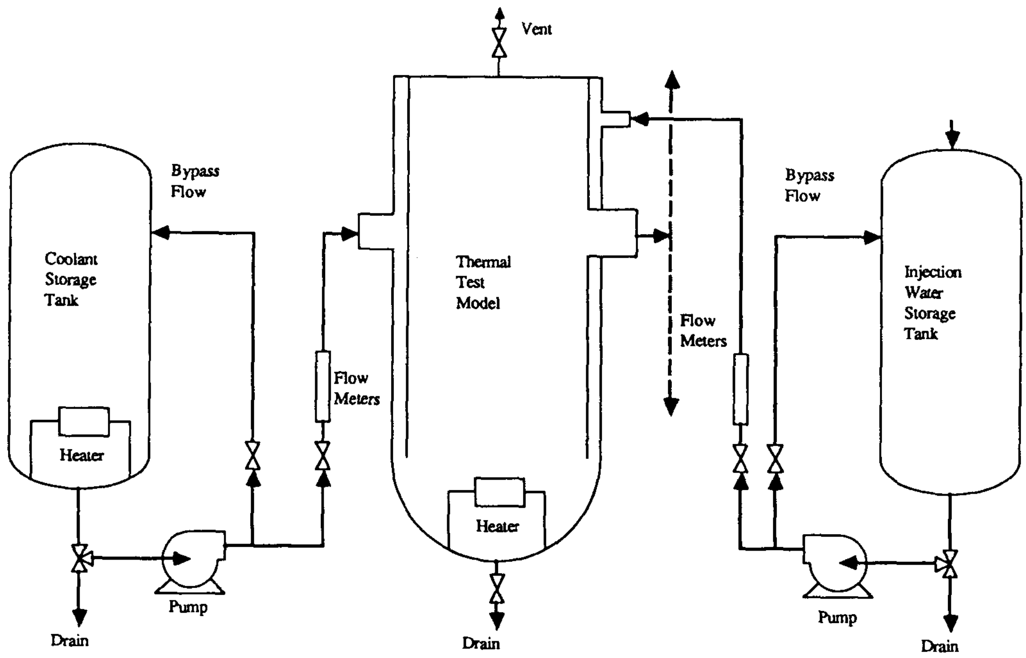

Fig. 4. Schematic Diagram of Thermal Mixing Test Facility

flows covering ranges of interest to the issue of PTS at atmospheric pressure. The test conditions for thermal mixing tests are also shown in Table 1.

3. Test Results and Discussion

3.1. Flow Visualization Tests

Individual flow visualization scenes were produced for eight test runs with the flow patterns in a 1/5-scale test model. Figure 5 shows a typical four-frame sequence of dyed DVI flow in the downcomer annulus. The DVI flow rate in this test was 0.17kg/s, and the coolant in the downcomer maintained at the lower level of the cold leg. The test lasted about 20 seconds of real time. This time was sufficiently long in most cases for the dye front to spread well over the field of view. The caption beneath each frame indicates the time in seconds relative to the arrival of the DVI fluid at the downcomer

Table 1. Test Conditions

Parameter	Prototype	Visualization Test	Thermal Test
System Pressure, MPa	8.84	0.1	0.1
Reactor Collant Temperature, °C	300	15	94
DVI Flow Rate, kg/s	40	0.17	0.167
		0.33	0.250
		0.50	0.333
		0.67	0.417
Coolant Level	Cold Leg Full	Cold Leg Full	Cold Leg Full
Loop Fow Rate, kg/s	~40	0	0.167
			0.417
DVI Temperature, °C	10	10(+salt)	10
Density Ration,($\triangle\rho/\rho_P$)	0.285	0.045	0.034
Range of Froude Number	1.0~1.5	0.81~3.20	0.92~2.29

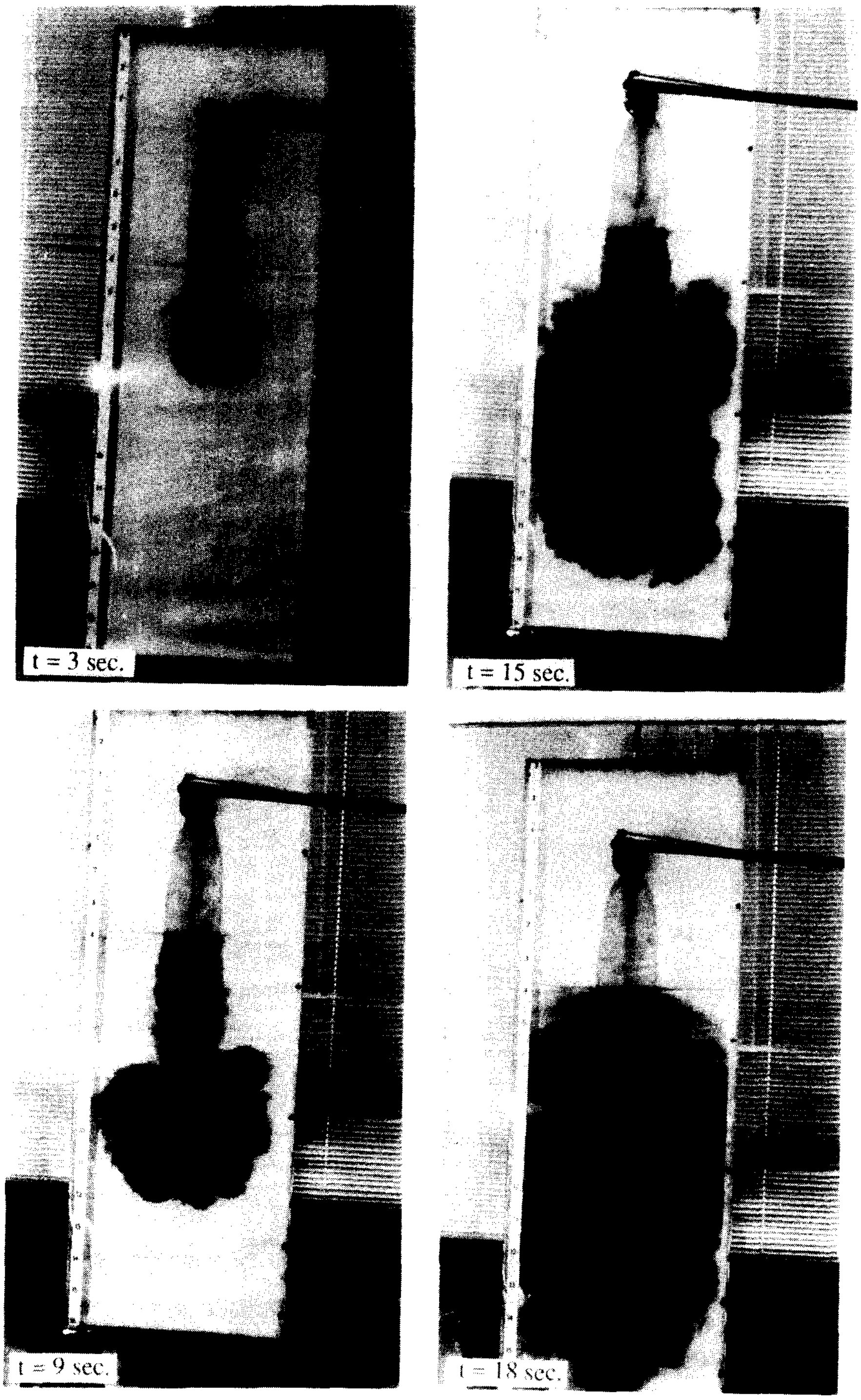

Fig. 5. Result of Flow Visualization Test, Cold Leg Coolant Level, 0.17kg/s DVI Flow Rate, 4.4% Salt Concentration (t: time after injection)

annulus. As shown in the pictures, the dyed DVI water falls directly down to the surface of the bulk coolant in the downcomer at earliest time. The gravity flow of DVI water spreads downward, with forming specific flow patterns in the bulk coolant. In other words, the initial part of the DVI flow in the coolant forms strong plume flow and then the plume flow developed toward the mixing development region which has relatively higher mixing rate. In the later part of the flow transient, the DVI flow turned into a chaotic well-mixed state. In brief, the flow patterns during transients exhibit three distinct regions: plume flow region, mixing development region, and well mixed region. It appears that the beltline of vessel was exposed to the coolant between the mixing development region and the well mixed region. Similar trends of flow patterns of the dye front were observed at the other DVI flow rates.

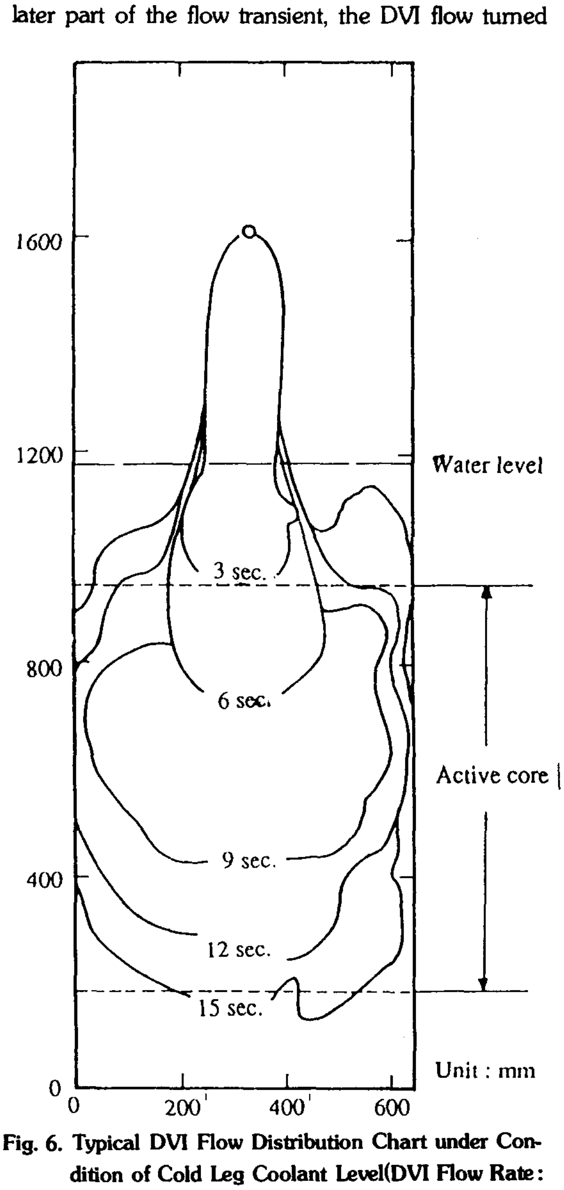

Fig. 6. Typical DVI Flow Distribution Chart under Condition of Cold Leg Coolant Level(DVI Flow Rate: 0.17kg/s)

The video tapes which recorded all visualization test runs were analyzed by an image processor to produce a time-dependent flow distribution chart of the dye front. Figure 6 shows the typical distribution chart of the dye front at every 3 seconds for the above test run. From this chart, the dye front velocity during the reansient can be obtained. The velocity of DVI flow at the mid-portion is about 0.10m/s during the first 3 seconds and then decreases to 0.06m/s during the next 3 seconds. The dye front line expands downwards as well as in the lateral direction.

Figure 7 shows the typical view of a visualization test under the condition of full liquid in the downcomer annulus. This test was performed with the DVI flow rate of 0.50kg/s. The test lasted about 25 seconds of real time. As seen in the pictures, the pattern of DVI flow under the condition of full coolant level in the downcomer was somewhat different in shape from those obtained in the tests under the cold leg coolant level condition. The DVI flow near the nozzle forms a lump of dyed liquid after DVI injection. The velocity of the DVI flow in the coolant was somewhat slower than in the tests under the cold leg coolant level condition. It seems that this is mainly the result of buoyancy effects. After forming a lump of injected liquid, the DVI flow spreads down widely toward the mixing development region. It then forms a long wide region of well mixed flow. There is no clear pattern of plume flow at the initial stage of DVI flow in this case. The beltline of the vessel was exposed to the intensive mixing region. Figure 8 shows the result of image processing for the above test run.

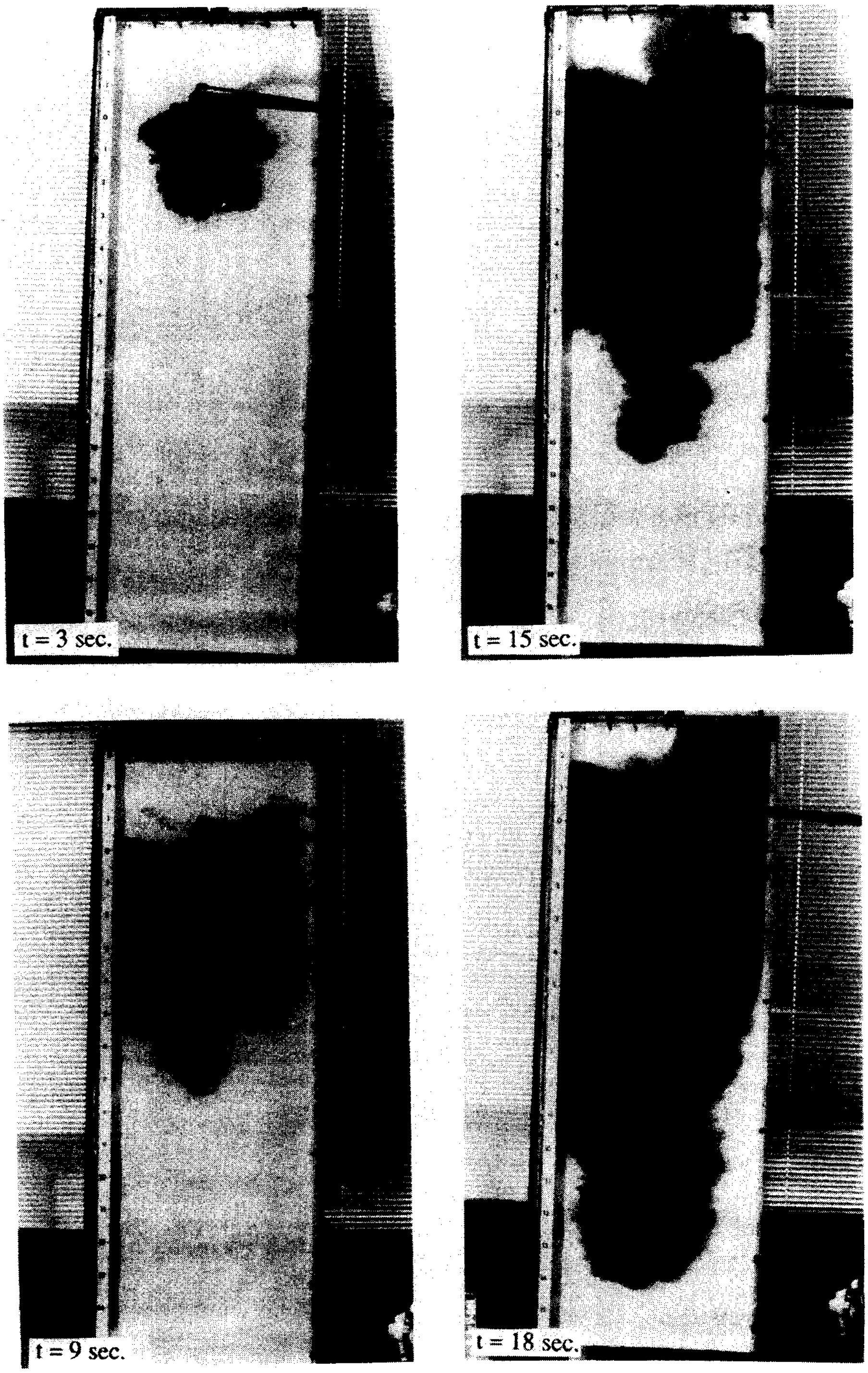

Fig. 7. Result of Flow Visualization Test, Full Coolant Level, 0.5kg/s DVI Flow Rate, 4.4% Salt Concentration (t: time after injection)

The centerline velocity of the plume in the downcomer can be easily measured using the velocity distribution chart which was drawn by the image processor. Kotsovinos[7] proposed the correlation for the plume velocity in the downcomer, V_p(in m/s), as follows :

$$v_p = C\,B^{1/3} \qquad (2)$$

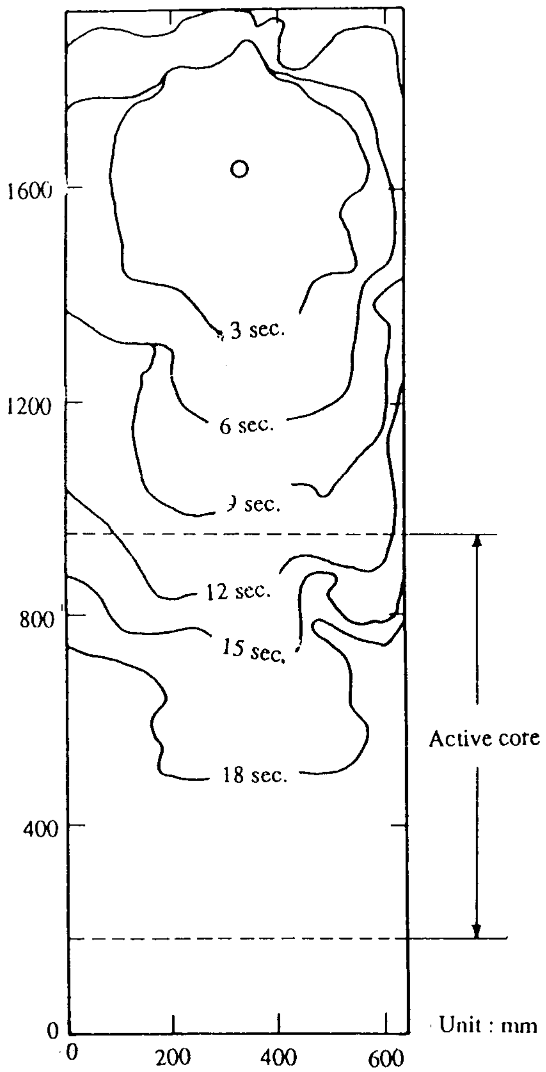

Fig. 8. Typical DVI Flow Distribution Chart Under Condition of Full Coolant Level(DVI Flow Rate:0.50kg/s)

where C is a constant. Kotsovinos suggested using C=1.66. The specific bouyancy flux, B, can be approximated as :

$$B = g(Q_{DVI}/S)(\rho_{DVI}-\rho_b)/\rho_b \qquad (3)$$

where Q_{DVI}=DVI volumetric flow rate(in m^3/s), and s=downcomer gap width(in m).

Figure 9 shows the measured dye front velocities in the downcomer as a function of the one-third power of the specific bouyancy flux for the case of cold leg coolant level and for the case of full coolant level. The dye front velocity is somewhat inportant with respect to PTS. Because it is an index of the fluid cooldown with unit time interval. These values were compared with the Kotsovinos correlation and with some data reported by Rothe et al.[5]. As seen in this figure, the constant C would be set equal to 0.72 for the case of cold leg coolant level, and to 0.40 for the case of full coolant level.

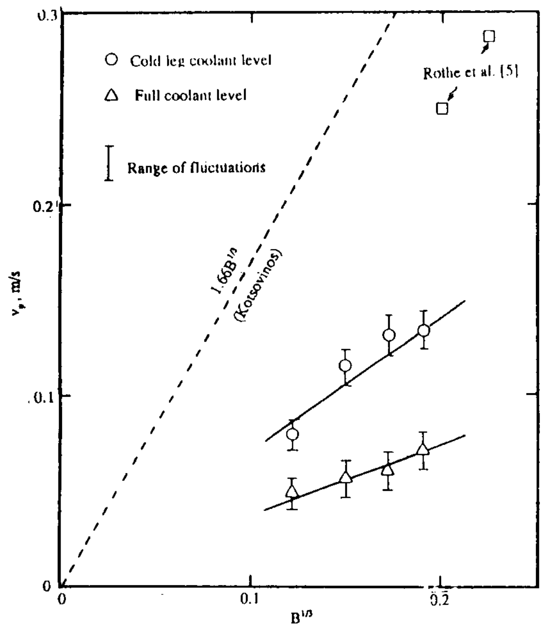

Fig. 9. Dye Front Velocities as a Function of $B^{1/3}$

3.2. Thermal Mixing Tests

A total of 12 tests were performed under conditions of cold leg coolant level with stagnant loop flow, and of full coolant level with loop flow. Figure 10 shows typical transient temperature data for the test under the condition of cold leg coolant level with 0.250kg/s DVI flow rate and stagnant loop flow. An exponential temperature decay occured from 94°C to 15°C during about 17 minutes. Temperature traces at three locations show some degree of stratification in the downcomer. Figure 11 illustrates the measurements of the transient temperature at the top level of the active core in the downcomer for the four DVI flow rates. In this figure, the steeper transient cooldown can be found at the higher DVI flow rate.

Figure 12 shows a comparison between the measured data and calculations obtained using the REMIX code [8] at the top level of active core with 0.250kg/s DVI flow rate. The REMIX code was developed on the basis of the regional mixing model (RMM). RMM provides a phenomenologically-based analytical description of the stratified flow and temperature fields resulting from high pressure safety injection in the stagnated loops of a PWR. The REMIX code was originally designed for cold leg injection. Therefore, the code was appropriately modified for DVI application. The key to the modification was to substitute the DVI nozzle for the cold leg in the calculation. A fictitious DVI line was used in the program equal in diameter to that of the cold leg. Also, cold stream temperature was set equal to DVI temperature, and cold stream height was set equal to DVI nozzle diameter. The transient temperature measurements are in good agreement with the predictions.

Figure 13 shows the downcomer fluid cooling transients at three different points under the condition of full coolant level with DVI flow rate of 0.250kg/s and loop flow rate of 0.167kg/s. Due to the limitation of water storage in the tank, each test was terminated at 200 seconds after DVI injection. The initial temperature exponentially drops to about 40°C at 200 seconds. It can be seen that the temperature data are somewhat scattered during the early part of the transient. The temperature measurements at the top point of the above test run were compared with the predictions with the COMMIX-1B [9] code as shown in Figure 14. The capability of COMMIX-1B includes steady state/transient, three-dimensional, and single-phase heat transfer and fluid flow analysis of nuclear reactor systems and normal and off-normal operating conditions. This code provides detailed local velocity and temperature fields for the problems under consideration. In the calculation, the one-equation turbulence model and the fully implicit scheme were employed. The code predictions of fluid temperature in the downcomer agreed well with the test data.

From the viewpoint of PTS, a small break LOCA condition may become important because of its potential for stagnation loop flow condition that could produce a significant cooldown. The transient temperature profile under the condition of cold leg coolant level with stagnated loop flow(in the case of the small break LOCA) in the C-E System 80+ reactor vessel was obtained with the REMIX code. It was assumed that the temperature of DVI flow was 10°C, and that the initial temperature of coolant in the downcomer was 300°C. This temperature profile is compared with the temperature measurements in the test model with 0.250kg/s DVI flow rate and stagnant loop flow in Figure 15. Temperature is nondimensionalized with respect to the bulk-to-DVI different temperature and the time scale is normalized respect to the characteristic mixing time, τ, which is defined as:

$$\tau = V_E / Q_{DVI} \tag{4}$$

where V_E = effective thermal mixing volume(in m^3)

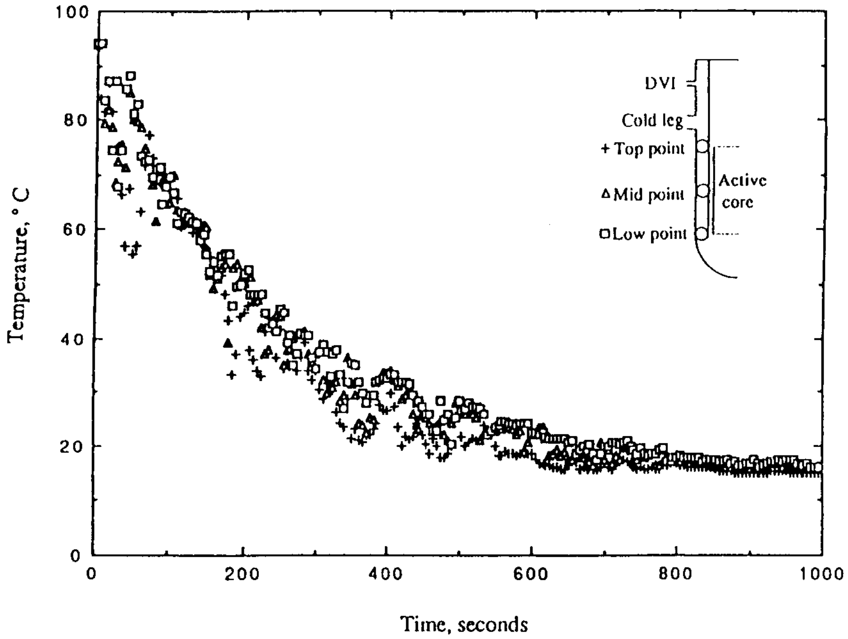

Fig. 10. Typical Temperature Measurements during Cooldown Transient under Condition of Cold Leg Coolant Level with Stagnant Loop Flow (DVI Flow Rate: 0.250kg/s)

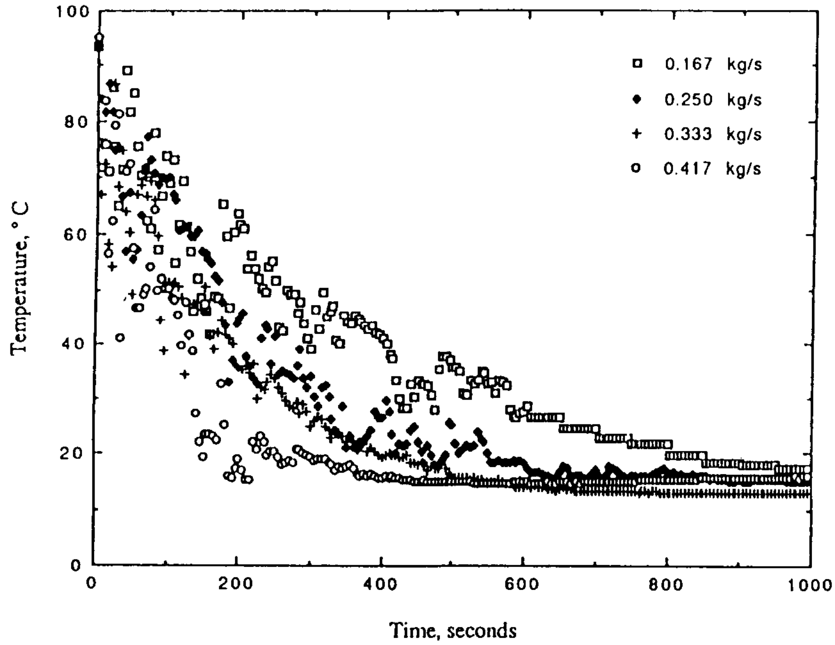

Fig. 11. Transient Temperature Measurements for Four DVI Flow Rates

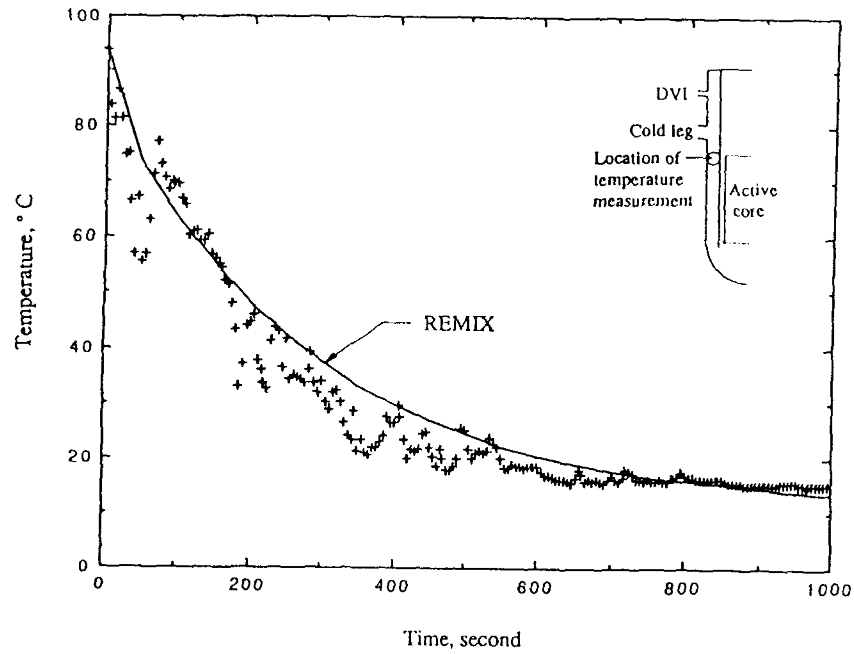

Fig. 12. Comparison Between Measured Data and Calculations by REMIX Code(DVI Flow Rat: 0.250kg/s)

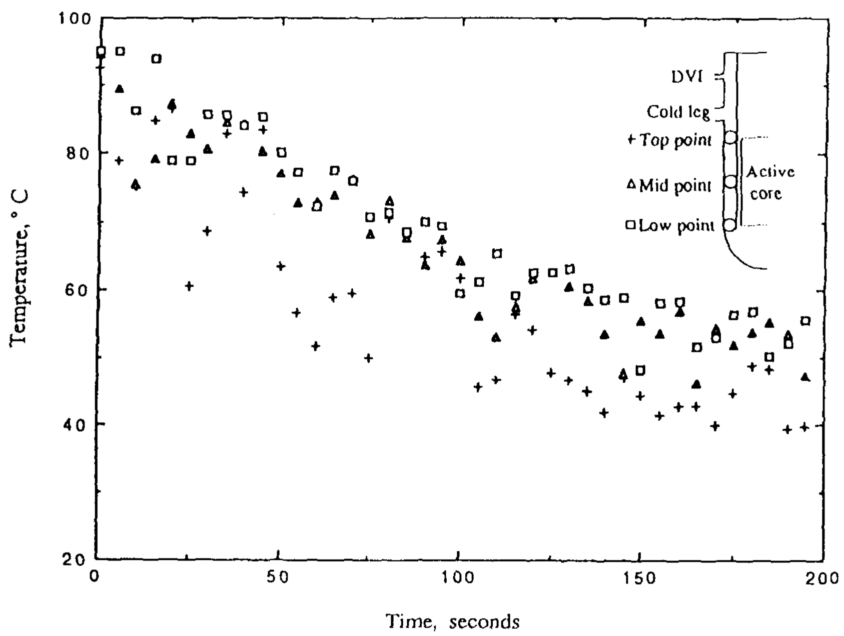

Fig. 13. Typical Temperature Measurements during Cooldown Transient under Condition of Full Collant Level with Loop Flow(DVI Flow Rate: 0.250kg/s, Loop Rate: 0.167kg/s)

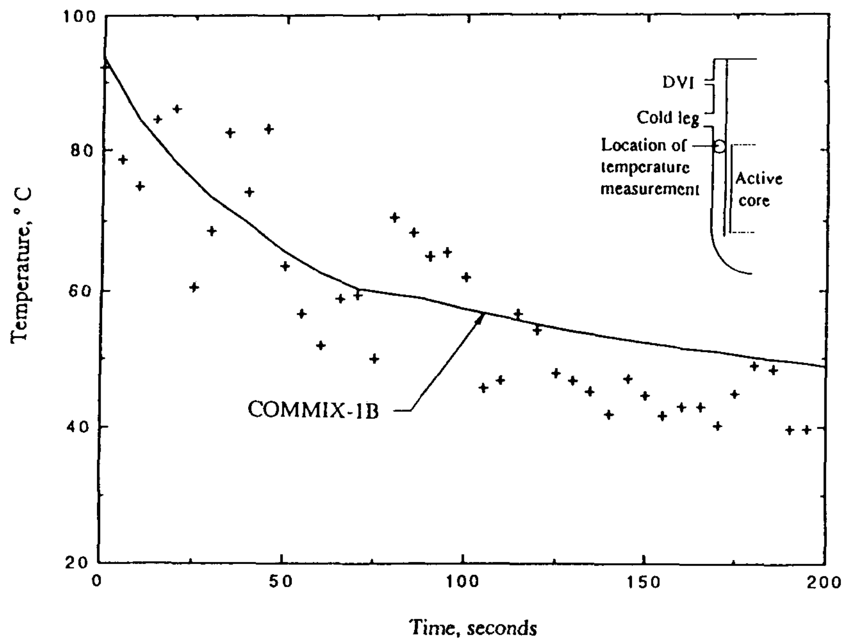

Fig. 14. Comparison Between Measured Data and Calculations by COMMIX-1B Code(DVI Flow Rate: 0.250kg/s, Loop Flow Rate: 0.167kg/s)

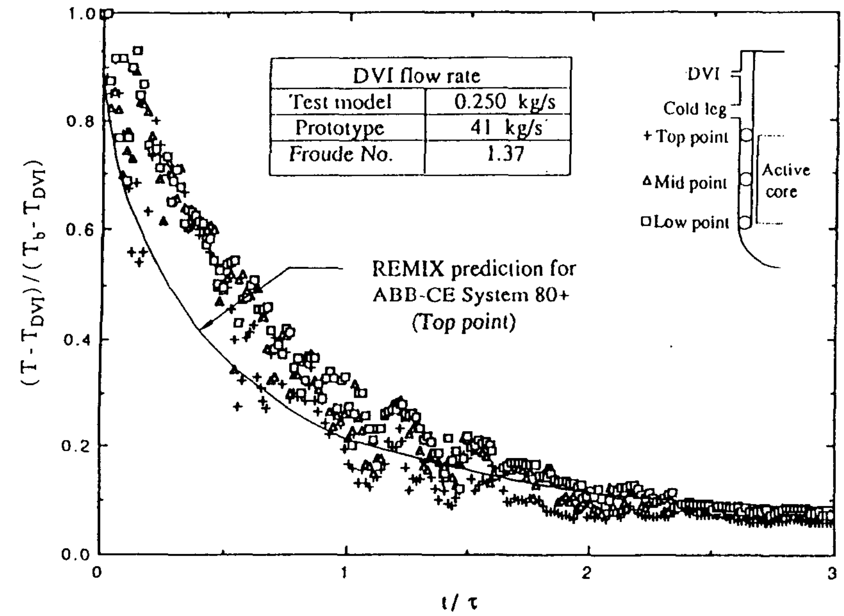

Fig. 15. Comparison of Temperature Transient Between Experimental Data and REMIX Predication for C-E System 80+

and Q_{DVI} = volumetric DVI flow rate(in m^3/s). The DVI flow rate in System 80+ was taken to correspond with the DVI flow rate at the test model. The temperature calculation for the prototype is very close to the temperature responses observed in the test model.

4. Conclusions

The following conclusions may be drawn from this work:

(1) Flow visualization tests with DVI have clarified the physical interaction between DVI fluid and primary coolant during transient cooldown.

(2) In the test condition of cold leg coolant level in the annulus, flow patterns during the initial part of the transient exhibit three distinct regions. In the case of full liquid in the annulus, however, there was no distinct period of plume flow during the flow transient. It appears that the vessel beltline was exposed to the coolant between mixing development region and well mixed region.

(3) Because of coolant stagnation in the reactor core, a significant temperature drop occured in the downcomer during the tests which simulated a small break LOCA. This may present the possibility of great PTS challenge to the vessel.

(4) Measured transient temperature profiles compare well with the predictions from the REMIX code for a small break LOCA and with the calculations from the COMMIX-1B code for a steam line break event.

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