Journal of the Korean Nuclear Society
Vol. 2, No. 1, March, 1970

《Original》

A Study on Coolant Mixing in Multirod Bundle Subchannels

Jong Hee Cha and Moon Haeng Cho

Atomic Energy Research Institute ,Seoul Korea

(Received March 13, 1970)

Abstract

A study was conducted on the coolant mixing between water flowing in two adjacent subchannels. Measurements were made of the quantity of mass transferred between a larger rectangular channel and a smaller triangular channel in a 19-rod fuel bundle under the conditions of single phase flow and air-water two-phase flow. The results of the experiments showed that the low mixing rate appears in single phase flow, and high mixing rate was measured in air-water two-phase flow. Mixing rate decreases with the increasing of air void fraction during the air-water flow. It seems that the high mixing rate in the air-water flow was caused due to adequate agitation of the chaotic air void.

요　　약

이 연구는 다봉속내에서의 인접유로간의 냉각재 혼합류를 실험적으로 다룬 것이다. 실험은 19봉속내의 사각형 유로와 삼각형 유로간의 혼합류를 단상 유동과 공기—물 이상 유동에 물질 전달량을 측정하여 얻고 있다. 실험결과는 단상 유동에서 낮은 혼합률을, 공기—물 이상 유동에서 큰 혼합률을 얻고 있으며 공기—물 유동에서의 혼합률은 공기 체적률의 증가에 따라 감소되고 있음을 나타내고 있다. 공기—물 이상 유동에서의 높은 혼합률은 공기류에 의한 충분한 교란효과 때문인것 같다.

INTRODUCTION

The advent of the nuclear age has created thermal and hydraulic problems never encountered in the past. Among these problems, the determination of coolant conditions in the subchannels of the reactor core array is an important phase in the thermal design of a power reactor. During the past decade, therefore, the studies of coolant redistribution problem in the multirod fuel bundle for both of single phase and two-phase flow were performed.

An imbalance occurs between the mass flow rate and enthalpy increasing rate at each subchannel of the fuel bundle when the bundle is centered in a circular tube because the ratio of the heat transfer surface area to the flow area is not equal for all subchannels. There is an interchange of flow through the gap between adjacent channels by the diversion cross flow and the random travel of the coolant. However, it is hard to determine the hydraulic local condition by means of theoretical calculation because of the complicated flow pattern especially in two-phase flow.

In order to analyze the mixing phenomena between the coolant flow passages, several investigations have been performed both of experimental and theoretical aspects. An old experimental work of the mixing problem was made by Shimazaki and Freede(1). They determined a sufficient degree of coolant mixing by concentration of injecting a chemical solution utilizing the seven equaldiameter wire wrapped rods. The similar work was made by Waters (2). Bishop et al. (3) determined the effective interchannel mixing flow experimentally for a 19-rod assembly using a chemical solution. They found that the mixing flow ratios were approximately 3.6 to 1 for wrapped and unwrapped fuel assemblies. Moyer(4) investigated the aspect of coolant mixing with the size of turbulent eddy diffusivity in the momentum and energy equations, and presented the turbulent eddy diffusivity in terms of Reynolds number and friction factor. Deissler and Taylor(5) have analytically studied the axial turbulent flow and heat transfer through banks of rods or tubes by the eddy diffusivity. Most of above works of mixing problem are only concerned with single phase flow. Recently, Cha(6) presented the experimental and analytical study on the coolant flow and enthalpy distribution in the multirod bundle subchannels during the single and two-phase flow. He developed a mathematical model of the cross flow mixing by using diversion and turbulent cross flow, and showed the good agreement with the experimental results.

Several computer codes have been developed to predict the coolant local conditions in fuel bundle assemblies by appropriate theoretical aspects. However, it seems some discrepancies still exist between experimental and predicted data from computer codes because of the uncertain parameters. The purpose of this work is to obtain the mixing flow data between two adjacent subchannels which were selected from 19-rod fuel bundle during the single phase and air-water two-phase flow. Measurements were made for the quantity of mass transferred between two adjacent channels by means of radioisotope tracer method.

EXPERIMENTAL

The experimental apparatus was designed and constructed in accordance with the purpose of the experimental investigation. The ranges of variables selected for study were: (1) mass flow rate, 0.5 to 2.5 x 10^6 lb/ft^{2}hr; (2) the void volume fraction, 0.5 to 0.89 at the water flow rate of 0.25 x 10^6 lb/ft^{2}hr during the air-water flow. The experimental apparatus is shown schematically in Fig. 1. Basically, the flow system consisted of a water and air-injection system, the tracer injection and sampling system, and the test section.

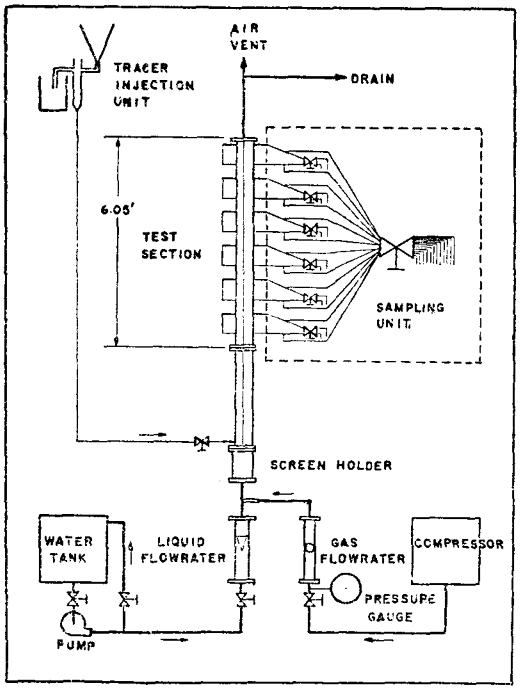

Fig. 1. Schematic Flow Diagram of Experimental Apparatus.

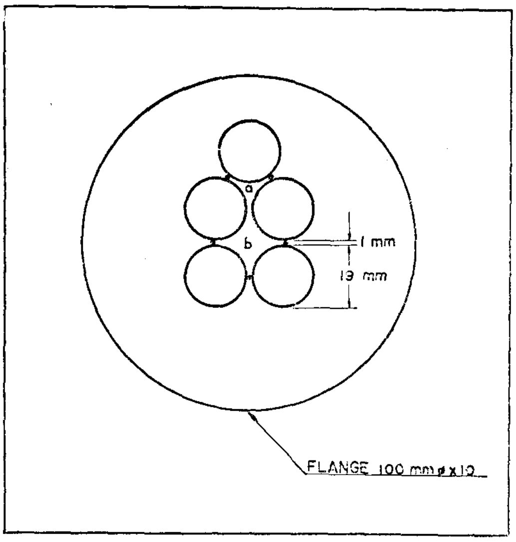

Fig. 2. Cross Sectional View of Test Section

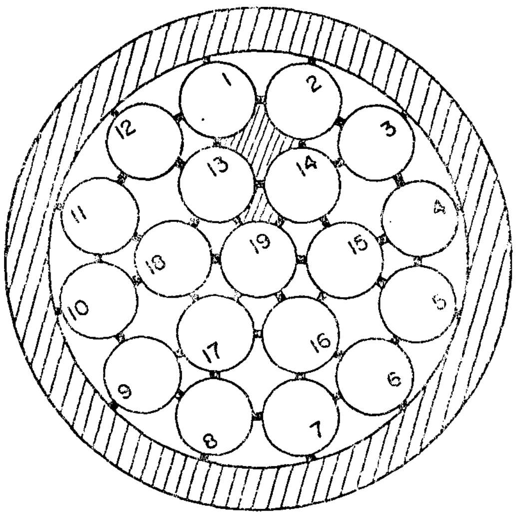

Fig. 3. Cross Sectional View of 19-Rod Bundle

Laboratory water was pumped from the water supply tank into the bottom of the test section through the flowmeter (Rotameter, range 2—20l/min.). The water flow rate was regulated by a main valve and a bypass system on the pump. After passing through the test section, the water was diverted to the drain by gravity. The air was obtained from the main laboratory 100 psi supply line. The air flowed through a air flowmeter and mixed with water in the connecting pipe between the water flowmeter and the screen holder. Homogeneous air-water mixing was expected to take place in the screen holder which was consisted of a series of screens.

The test section was composed of five 19 mm OD copper pipes which are arranged as shown in Fig. 2 so as to adjoin a larger rectangular subchannel and a smaller triangular one. Hydraulic diameters of larger and smaller subchannels are 0.31 and 0.17 in, respectively. The rod to rod spacing is 0.04 in. At intervals of 1 foot, six sampling points were located in each subchannel at the upper part of the test section. In the lower part of the test section, there was not allowable cross flow between two adjacent channels since the gap of rods was blocked by soldering. The tracer injection points were located at the bottom of the lower test section. The typical 19-rod fuel bundle is shown in Fig. 3, and indicated the selected two adjacent subchannels.

The tracer was K_2CrO_4 solution, that the radioisotope element Cr^{51} emits gamma ray of 0.32 Mev and has the half life of 27.8. days. The relative concentration of each sample was measured by counting the emitted gamma ray using a scaler (Model 202, Nuclear Chicago). The counting was conducted 5 times, 1 minute each time, for every sample.

The compressor which supplied the laboratory air had a magnetic switch and controlled the air pressure between the range from 35 psig to 55 psig. Because the air pressure in the flow system droped from that in the air supply pipe line, the volume of air in the flow loop system was calculated with the gas equation.

The tracer was injected by gravity during the appropriate time interval. Each of 6 sampling valves made of lucite had two openings so that samples from two corresponding points may be taken simultaneously. Sampling was conducted 3 times at each experimental run, and every sample was taken 2 cc and counted by the scaler. During the air-water flow, air was blowed into the loop after beginning of water supplying.

The flow rate of water was kept 0.25 x 10^6 lb/ft^2hr, and the air flow rate was varied during the air-water flow.

RESULTS AND DISCUSSION

The experimental data consist of 13 points in the single phase flow, and 12 points in the air-water flow. These were conducted with two adjacent test channels which were selected from 19-rod fuel bundle having length of 6 feet, at atmospheric pressure, and mass velocities of 0.5, 1.0, 1.5, 2.0, and 2.5 x 10^6 lb/ft^2hr for single phase flow, and 0.25 x 10^6 lb/ft^2hr of water flow for air-water flow. The void fraction during the air-water flow was varied from 0.5 to 0.89.

Table 1. Concentration Ratio with Relative Length for Water Flow

Run No.	Flow rate 10^6lb/ft^2hr	Concentration Ratio C_b/C_a at Relative Length of 0.17	0.33	0.50	0.67	0.83	1.00
1	0.5	0.0171	0.0375	0.0755	0.1161	0.1674	0.2430
2	1.0	0.0171	0.0426	0.0736	0.1211	0.1208	0.2633
3	1.0	1.0162	0.0419	0.0739	0.1181	0.1644	0.2487
4	1.0	0.0161	0.0441	0.0772	0.1232	0.1742	0.2821
5	1.5	0.0157	0.0398	0.0692	0.1195	0.1620	0.2645
6	1.5	0.0155	0.0420	0.0690	0.1159	0.1567	0.2553
7	1.5	0.0164	0.0394	0.0710	0.1177	0.1621	0.2550
8	2.0	0.0174	0.0434	0.0717	0.1189	0.1595	0.2560
9	2.0	0.0171	0.0436	0.0710	0.1184	0.1606	0.2641
10	2.0	0.0176	0.0449	0.0725	0.1240	0.1580	0.2630
11	2.5	0.0170	0.0430	0.0719	0.1221	0.1607	0.2511
12	2.5	0.0165	0.0448	0.0721	0.1164	0.1579	0.2500
13	2.5	0.0157	0.0445	0.0728	0.1223	0.1600	0.2547

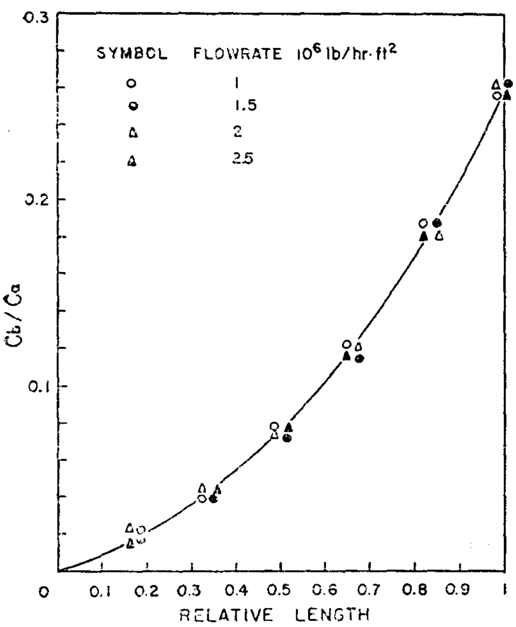

Fig. 4. Concentration Ratio with Relative Length for Water Flow

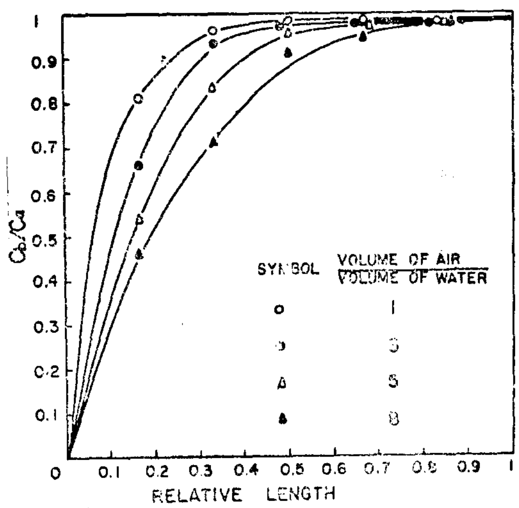

Fig. 5. Concentration Ratio with Relative Length for Air-Water Flow.

A plot of the concentration ratio of tracer with the relative length of test section for the water flow is shown in Fig. 4 and the concentration ratios are tabulated in Table 1. The concentration ratio, C_b/C_a is the ratio of concentration of tracer in channel b to that in channel a. The figure represents the increase of concentration ratio with increasing of length. Fig. 5 shows the concentration ratio with the relative length of test section for the air-water two-phase flow, and the tabulated data are shown in Table 2.

Table 2. Concentration Ratio with Relative Length for Air-Water Fow at 0.25 x 10^6 lb/ft^{2}hr Water Flow

Run No.	Void Fraction	Concentration Ratio C_b/C_a at Relative Length of				
		0.17	0.33	0.50	0.67	0.83
14	0.50	0.7824	0.9587	0.9853	0.9875	0.9831
15	0.50	0.8317	0.9672	0.9871	0.9886	0.9812
16	0.50	0.8040	0.9679	0.9871	0.9888	0.9850
17	0.75	0.6548	0.9280	0.9767	0.9838	0.9765
18	0.75	0.6872	0.9340	0.9672	0.9821	0.9774
19	0.75	0.6389	0.9286	0.9781	0.9814	0.9793
20	0.83	0.5027	0.8259	0.9658	0.9760	0.9845
21	0.83	0.5382	0.8335	0.9583	0.9782	0.9896
22	0.83	0.5440	0.8444	0.9598	0.9733	0.9875
23	0.89	0.4780	0.7357	0.9088	0.9547	0.9786
24	0.89	0.4772	0.7203	0.9237	0.9482	0.9773
25	0.89	0.4242	0.6755	0.9141	0.9575	0.9756

These data show extremely higher mixing rate compared with liquid phase flow. It seems clear that the mixing flow between adjacent subchannels was affected by the chaotic motion of air void, and the higher mixing rate was caused due to the agitation effect of voids. Petric(7) showed the visual aspect of chaotic air void flow during his air-water two-phase flow experiments. It is apparent that the variation of mixing ratio depends on the air void fraction during the air-water flow. Fig. 5 shows that the mixing rates decrease with the increasing of void fraction.

In the two-phase flow tests, the experimental data of concentration ratio between channel a and b were only concerned with liquid phase. However, it could be indicated the general trend of mixing flow between adjacent subchannels in the air-water flow. Most of above data, C_b/C_a, were taken by injecting the radioisotope into the channel a. It was almost similar results for injecting into the channel b according to some tests.

One may write a mass balance for a differential length of the channel dL

$$-m_a dC_a = w(C_a - C_b)\, dL \qquad (1)$$

and a mass balance on the entire length of the channel

$$m_a(C_{ai} - C_{ao}) = m_b(C_{bo} - C_{bi}) \qquad (2)$$

where m is the coolant flow rate per unit area per unit time, C is the concentration (or radioactivity of tracer), and where w is the mixing cross flow rate per unit length of channel. Subscripts a, b, i, and o refer to the channel a, channel b, inlet condition, and outlet condition.

Integrating Eq. (1) and solving with Eq. (2), we obtain

$$w = \frac{m_a m_b}{L(m_a + m_b)} = \frac{(C_{ai} - C_{bi}) - (C_{ao} - C_{bo})}{\dfrac{(C_{ao} - C_{bo}) - (C_{ai} - C_{bi})}{ln((C_{ao} - C_{bo})/(C_{ai} - C_{bi}))}}$$

Presented in Table 3 are the cross flow rates which are calculated from Eq. (3) for the single phase flow.

Table 3. **Cross Flow Rates for Single Phase Flow (lb/ft-hr)**

Run No.	Mass Flow Rate (10^6 lb/ft^2 hr)	Cross Flow Rates at Relative Length of					
		0.17	0.33	0.50	0.67	0.83	1.00
1	0.5	46	55	94	94	111	153
2	1.0	47	67	76	110	87	182
3	1.0	45	67	79	102	100	171
4	1.0	44	73	105	82	110	222
5	1.5	43	64	73	117	92	203
6	1.5	43	69	67	109	89	200
7	1.5	48	60	78	108	96	188
8	2.0	46	63	70	109	88	195
9	2.0	47	69	68	109	92	209
10	2.0	49	71	68	118	74	217
11	2.5	47	63	78	116	84	201
12	2.5	46	74	75	103	90	187
13	2.5	44	75	77	114	82	192

Cha(6) illustrated the representation of the assumed diversion and turbulent mixing flow between adjacent channels in his analytical model. The diversion mixing flow is caused by actual redistribution resulting from pressures trying to equalize as the coolant passes through the bundle. The turbulent mixing flow is the random travel of the coolant across the gap between adjacent channels.

The diversion mixing flow could be calculated by momentum equation associated with mass balance. At the present time, however, there is no analytical method to determine the turbulent mixing flow. According to the numerical calculation by using momentum equation, the values of diversion cross flow rate are in the range of 1 to 2 lb/ft^{2}hr for the Run no. 2. Then it is believed that the major part of cross flow rate in Table 3 consists in turbulent mixing flow.

CONCLUSIONS

The conclusions that can be made from this investigation are as follows.

The values of mixing rate for liquid single phase flow were generally lower than the case of air-water two-phase flow. It was found that there was no significant variation of mixing flow as a function of coolant flow rate in the range of this work. The mixing rate gradually increased with the length of test section.

The data of this work give the excellent mixing effect during the air-water flow. It was believed that this higher mixing rate was caused due to adequate agitation by the motion of air voids. It appears that the amount of mixing rate decreases with increasing of air void fraction. At high void fraction region, it seems the annular flow forms, and it tends to decrease the mixing effect.

Finally, the numerical values of mixing flow rate could be obtained by using tracer method for the liquid single phase flow, and the amount of mixing flow would, mainly, be consisted by turbulent mixing flow.

REFERENCES

1. T.T. Shimazaki and W. J. Freede, Heat Transfer and Hydraulic Characteristics of the SRE Fuel Element, TID-7529 (Pt. 1) Book 1, pp. 273-296, 1956

2. E. D. Waters, Fluid Mixing Experiments with a Wire-Wrapped 7-Rod Bundle Fuel Assembly, General Electric Co., Hanford Laboratory, HW-70178 Rev., 1963
3. A. A. Bishop, P. A. Nelson, and L. S. Tong, Coolant Mixing in a 19-Rod Fuel Assembly, Transactions of the American Nuclear Society, Vol. 4. No. 1, p. 43, 1961
4. C. B. Moyer, Coolant Mixing in Multirod Fuel Bundles, RISO-125, Danish Atomic Energy Commission, Research Establishment, 1966
5. R. G. Diessler and M. F. Taylor, Analysis of Axial Turbulent Flow and Heat Transfer through Banks of Rods or Tubes, TID-7529 (Pt. 1) Book 2, pp. 416–461, 1957
6. J. H. Cha, The Coolant Flow and Enthalpy Imbalance in Multi-Rod Bundle Subchannels, J. of the Korean Society of Mech. Engrs., Vol. 9, No. 4, pp. 1-26, 1969
7. M. Petric, Two-Phase Air-Water Flow Phenommena, ANL-5787, Argonne National Laboratory, 1958