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STUDIES OF MIXING IN THE LOWER PLENUM OF A
QUARTER-SCALE FLOW MODEL OF THE PWR REACTOR

by

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STUDIES OF MIXING IN THE LOWER PLENUM OF A QUARTER-SCALE FLOW MODEL OF THE PWR REACTOR

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Mixing in the lower plenum of a quarter-scale air-flow model of the PWR reactor was studied by use of SO_2 as a gaseous tracer in air entering one inlet. The concentration of SO_2 in each of the 145 simulated fuel clusters was determined under various operating conditions, and from these concentrations the extent of mixing was determined. It was found that flow from the traced inlet impinged on the bottom of the flow baffle and passed directly upward through simulated clusters in the quadrant above the inlet. The concentration of air from this inlet varied from as much as 90 per cent, above the center of impaction of the inlet jet on the flow baffle, to about 40 per cent, near the edges of the quadrant. The general appearance of isogram plots indicated that flow in each quadrant was similar, with high concentrations of coolant from the inlet under the quadrant. Mixing improved outside the area of direct impaction, approaching complete mixing around the periphery of the model core, where much of the coolant emerged from the shield passages. In two tests under nominally similar conditions, mixing data were reproduced within 5 per cent on a scale in which concentration of air from the traced inlet varied from 0 to 100 per cent.

INTRODUCTION

In order to evaluate the effects which may result in putting into service a nonoperating loop which contains water at a lower temperature than that in the operating loops, it is necessary to know the amount of mixing which takes place in the lower plenum chamber. This report presents data on mixing in the lower plenum of a quarter-scale flow model of the PWR reactor that is being designed at the Bettis Laboratory of the Atomic Energy Commission operated by the Westinghouse Electric Corporation. The flow model was designed at the Bettis Laboratory and built at the Aviation Gas Turbine Division of Westinghouse. In model studies, air was used to simulate water flow in the prototype. This is the second report describing flow studies conducted at Battelle using this model. A previous report, BMI-1141, "Studies of Flow Distribution in the Core of a Quarter-Scale Flow Model of the PWR Reactor" was issued on October 19, 1956.

APPARATUS AND TEST PROCEDURES

The Quarter-Scale Flow Model

The quarter-scale flow model was designed to simulate flow conditions throughout the PWR reactor with the exception of those within the fuel

assemblies; these were simulated with orificed tubes having proper flow resistances. It was constructed of aluminum and stainless steel throughout, except for the upper and lower domes, which were constructed of glass-fiber-reinforced plastic.

Figure 1 is a photograph of the quarter-scale flow model set up for tests. Four blowers at the left supplied air for tests and the large manometer board at the right was used to record pressures throughout the model. The highest air flow used in the quarter-scale model was 5.33 lb per sec at 5.2 psi.

Figure 2 is a vertical section of the quarter-scale flow model, showing the general arrangement of the pressure shell, the inlets and outlets, the thermal shields, the flow baffle, the core, the control-rod guides, the hold-down barrel, and the internal instrumentation.

Figure 3 is a horizontal section of the model, showing arrangement of the thermal shields, the core fuel clusters, and the shield-passage instrumentation.

Air, simulating the coolant, entered through two or more of the inlets at the bottom of the model. About 85 per cent of the coolant flowed upward through the perforated flow baffle under the core; the baffle pressure drop was designed to force about 15 per cent of the coolant through the thermal-shield passages at the outer periphery of the model. Coolant from these parallel paths mixed below the core, then passed upward through the core. In the model, the core fuel clusters were simulated by round tubes, each containing an orifice for measurement of flow through the tube and a restricting orifice at the tube inlet for control of flow. The core was divided into five regions. Flow through all simulated fuel clusters in each region was equal but flow to different regions differed. Above the core was a large plenum space through which the control-rod guides passed, and a hold-down barrel containing 28 holes through which coolant passed to reach the four outlets.

Model Setup and Operation

The model was set up to permit close control of flow to individual inlets and outlets and to minimize the leakage of SO_2 tracer from the model exhaust into the room. The general arrangement of test equipment is shown in Figure 1. Four blowers, connected in series, provided air at pressures to 6 psi and flow rates to 5.5 lb per sec. Air entered these blowers from the room through glass-fiber filters and an orifice for measuring total flow and, after compression, entered the model through vertical approach piping and 90-deg elbows to simulate the prototype installation. A flow-measuring nozzle was installed at each inlet to measure flow and to determine when flow to inlets was equal. Flows to individual inlets were adjusted by

FIGURE 1. PHOTOGRAPH OF QUARTER-SCALE FLOW MODEL OF
PWR REACTOR INSTALLED FOR AIR-FLOW STUDIES

FIGURE 2. QUARTER-SCALE FLOW MODEL OF PWR REACTOR -- VERTICAL SECTION

FIGURE 3. QUARTER-SCALE FLOW MODEL OF PWR
REACTOR — HORIZONTAL SECTION
THROUGH CORE

adjusting the depth of insertion of 3/8-in. rods into the air streams in the elbows. In tests with simulated operation with less than four loops, plates were installed between flanges of inactive inlets and outlets.

Outlets were fitted with short flow-measuring sections, as shown in Figure 1. However, for mixing studies, these were connected to 8-in. exhaust piping which carried the contaminated air to the building roof and kept the background level of SO_2 in the room low.

Pressure taps from the 145 measuring orifices in the core were connected to a specially constructed manometer board having 360 tubes, each suitable for measurement of pressures up to 170 in. of water. The manometer board consisted of six well-type manometers, each having one leveling tank and many manometer tubes. Each manometer tube extended from the model to the top of the manometer, then passed down through the manometer and was connected to a header at the bottom. Manometer tubes were of translucent polyethylene plastic.

Instrumentation and Test Procedure

Mixing studies were conducted by injecting measured concentrations of SO_2 into Inlet 2-3, and determining the concentration of SO_2 in air passing through each of the 145 simulated fuel clusters in the model core. The SO_2 was supplied from a pressurized gas cylinder through a pressure regulator and a Flowrater-type flowmeter, which controlled and measured the flow. Because of the extremely low volume of SO_2 required, the gas was then discharged into a small chamber where it was mixed with a much larger quantity of compressed air, and the mixture was injected into the model inlet piping. The injector consisted of four 1/4-in. stainless steel tubes, each with five holes of 0.012 in. diameter, and was located in the horizontal run of pipe 11 ft upstream from the model inlet. The twenty injector holes were located at centers of equal areas in the inlet duct, and the pressure drop across the injector was held at 4.9 psi. With this arrangement, deviations from the average concentration of 10 ppm of SO_2 at the model inlet were generally less than 5 per cent.

Samples of air from each of the 145 simulated fuel clusters were bled continuously from the upstream pressure taps of orifices installed in the model for measurement of flow. The polyethylene manometer tubes previously used for pressure measurement were detached from the headers at the bottom of the manometer panel and allowed to vent air continuously into an exhaust duct containing holes into which all tubes could be inserted when not in use. A sample for analysis was drawn from each manometer tube in turn, and analyzed immediately in a Titri-log recording instrument which recorded concentration of SO_2 . With this procedure, it was possible to traverse the entire core in about half a day, with frequent checks of inlet

concentration and of background level in a second inlet which nominally contained no SO₂.

The Titri-log recording instrument which was used to measure SO₂ concentration is manufactured by the Consolidated Engineering Company. In this instrument, SO₂ or other oxidizable sulfur compounds are titrated with electrolytically generated bromine at a potentiometric balance point. A feedback amplifier controls the rate of generation of reacting bromine above a set reference level so that it is at all times equal to the rate of absorption of SO₂ in the titration cell. The current flow in the electrolytic cell serves as a measure of the concentration of SO₂. The instrument scale has a range 0 to 10 ppm of SO₂ with a reading accuracy of ± 1.5 per cent of full-scale reading and is sensitive to a change in concentration of 0.1 ppm. The instrument requires about 10 sec to reach equilibrium after a change in inlet concentration.

RESULTS OF MIXING STUDIES

Test Data

The purpose of mixing studies using air was to investigate mixing in the bottom plenum space under the following operating conditions:

- (1) Admission of water at a lower temperature to a third loop when two opposed loops are operating. This condition was simulated in Test 57.
- (2) Admission of water at a lower temperature to a third loop when two adjacent loops are operating. This condition was simulated in Test 58.
- (3) Admission of water at a lower temperature through the fourth loop when three loops are operating. This condition was simulated in Tests 59 and 60.

Figure 4 shows mixing data for Test 57 with Inlet 2-3 plus two opposed loops in operation. The figure represents a cross section of the core of the flow model, the numbers indicating the percentage of flow in each simulated cluster which came from Inlet 2-3. With perfect mixing in the lower plenum, a value of 33.3 per cent would be obtained in every cluster. It will be noted, however, that concentrations in the quadrant of Inlet 2-3 were generally high and peaked near the center of the quadrant where the jet from this inlet impinged on the flow baffle. Above this point of impingement, values of 90 per cent and above were measured in six clusters, with a peak value of 96 per cent.

Figure 5 is an isogram plot of the data in Figure 4. In this plate the outline of the impinging jet from Inlet 2-3 is evident, with concentrations of air from this inlet dropping rapidly with distance from the center of the jet. Similar action of the other two inlet jets is evident from the very low concentrations of air from Inlet 2-3 which appear at the centers of impaction of these jets.

Figures 6 and 7 show mixing data for Test 58 using Inlet 2-3 and two adjacent loops. The different arrangement of operating inlets resulted in a somewhat different pattern, with lower peak concentrations. The highest concentration of air from Inlet 2-3 measured was 91 per cent, with four values of 82 per cent and above. Comparison of Figure 5 and Figure 7 show that the flows from the two adjacent operating loops merged to form a rather large area of low concentration, and that concentration was highest in the quadrant above Inlet 2-3, as might be expected. Mixing over a large part of the core was good with values approaching 33 per cent.

Figures 8 and 9 show mixing data for Test 59, using Inlet 2-3 plus the other three loops. With this configuration, one fourth of the flow entered Inlet 2-3, so that perfect mixing would result in a concentration of 25 per cent of air from Inlet 2-3 in each simulated cluster. Again, the areas of impaction of inlet jets are clearly evident with a large area of low concentration where the jets from the three operating loops converge, and an area of high concentration above Inlet 2-3. With this configuration, there were four clusters in which concentrations of air from Inlet 2-3 were 76 per cent and above, with the maximum value at 83 per cent.

Figure 10 shows mixing data for Test 60. This test was run under conditions similar to those in Test 59 to check reproducibility of data. Comparison of Figure 10 with Figure 8 shows that all data are consistent and that the differences in measured percentages of flow from Inlet 2-3 do not exceed 5 per cent in any cluster.

Estimated Mixing Pattern in Lower Plenum

Figure 11 shows the estimated mixing pattern in the lower plenum of the air-flow model for Test 60, with four loops operating. The flow from Inlet 2-3, which contains the SO_2 tracer, is shown as a classical jet with turbulent diffusion proceeding at a rate such that the surrounding fluid reaches the axis four diameters from the inlet. This pattern is commonly accepted as being typical of all circular jets at high Reynolds numbers. In Figure 11, the 3.5-in.-diameter jet travels about 14 in., or 2.5 diameters, before it impinges on the flow baffle. Thus, the core of the jet has not yet been diluted by flow from other inlets on reaching the flow baffle. This undiluted core accounts for about 15 per cent of the flow in the jet. As the jet passes through the flow baffle, it is broken up into many small jets.

Numbers in each simulated fuel cluster show percentage of air from Inlet 2-3. Remaining air comes from other inlets

FIGURE 5. ISOGRAM PLOT OF MIXING DATA FOR TEST 57 USING INLET 2-3 PLUS TWO OPPOSED LOOPS

Numbers show percentage of air from Inlet 2-3

Numbers in each simulated fuel cluster show percentage of air from Inlet 2-3. Remaining air comes from other inlets

FIGURE 7. ISOGRAM PLOT OF MIXING DATA FOR TEST 58 USING INLET 2-3 PLUS TWO ADJACENT LOOPS

Numbers show percentage of air from Inlet 2-3

FIGURE 8. MIXING DATA FOR LOWER PLENUM OF PWR FLOW MODEL USING INLET 2-3 PLUS THREE LOOPS, TEST 59

Numbers in each simulated fuel cluster show percentage of air from Inlet 2-3. Remaining air comes from other inlets

FIGURE 9. ISOGRAM PLOT OF MIXING DATA FOR TEST 59 USING INLET 2-3 PLUS THREE LOOPS

Numbers show percentage of air from Inlet 2-3

Numbers in each simulated fuel cluster show percentage of air from Inlet 2-3. Remaining air comes from other inlets

FIGURE II. ESTIMATED MIXING PATTERN IN LOWER PLENUM OF PWR FLOW MODEL USING INLET 2-3 PLUS THREE LOOPS, TEST 59
 Numbers show percentage of flow from Inlet 2-3; remaining air comes from other inlets.
 Numbers below core are estimated; those above core are measured values from Test 59.

Each of these, in turn, becomes fairly well diffused with immediately surrounding fluid as it passes upward to the inlets of simulated fuel clusters in the model. All dilution of the core of the jet probably takes place above the flow baffle.

The curve plotted above the core in Figure 11 shows measured values of concentration of air from Inlet 2-3 across the core, from Figure 8. These values appear to support the validity of the estimated flow pattern in the lower plenum. The numbers shown in the lower plenum, and for flow from the shield passages, are estimated concentrations of air from Inlet 2-3 based on an estimated diffusion gradient from the jet, and on values measured in the core, from Figures 8 and 9.

The axis of the jet in Figure 11 was made as a straight-line extension of the axis of the inlet nozzle. Data in Figures 5 through 9 show that other inlet jets may bend the jet somewhat; if the opposing jet is not in operation, the jet extends closer to the center of the reactor, and if an inlet at one side is not operating, the jet will be diverted slightly in that direction.

Analysis of Data Error

The errors which might influence measured values of SO_2 concentration and calculated values of the concentration of air from Inlet 2-3 occurring throughout the core arise from three sources: error in determining SO_2 concentration with the Titrilog recorder, fluctuation of mean SO_2 concentration with time, and nonhomogeneity of the SO_2 air mixture in Inlet 2-3. Traverses of SO_2 concentration in Inlet 2-3, using the same instrumentation and techniques as used for traverses of the core, would be subject to exactly the same sources and values of error as would core traverses. However, all values of SO_2 concentration measured in Inlet 2-3 should be equal, providing a means of evaluating test error. It is estimated that the maximum values of these errors are: instrument error, ± 1.5 per cent; fluctuations, including instrument error, ± 2.5 per cent; and nonhomogeneity, ± 5 per cent.

A ten-point traverse of Inlet 2-3 was run immediately proceeding each test. Analysis of data from five traverses shows that the maximum errors found in 50 data points were -8 per cent and $+6$ per cent. For 96 per cent of the data points, error was less than ± 6 per cent, and for 80 per cent of the data points error was less than ± 4 per cent. It appears probable that similar ranges of errors apply to the core data shown in Figures 4 to 10.

The values of peak concentrations found at the center of the impaction area above Inlet 2-3 were generally consistent with operating conditions, and were substantiated by the low values of dilution indicated in corresponding areas above clean-air inlets.

Approach to Similarity of Mixing in Model and Prototype

The evaluation of results of mixing studies in the quarter-scale air-flow model requires consideration of differences in scale, Reynolds number, and properties of fluids used. In the prototype, water is used as a coolant, and a typical Reynolds number, in an inlet nozzle, would be 30,000,000. In the model, air simulates coolant flow and a comparable Reynolds number is 450,000.

Differences in fluid properties affect molecular diffusion rates, molecular conduction rates, and through the Reynolds number, the turbulent diffusion effects. In any turbulent system, the turbulent diffusion effects are so much larger than molecular effects that molecular effects can be ignored without introducing significant error. Thus, it may be concluded that the only significant effects of differences in fluid properties are those which influence the Reynolds number, so that flow similarity would result in similarity of mixing.

The value of Reynolds number in the model inlets at 450,000 is high enough to assure a close approach to dynamic similarity even though the prototype Reynolds number is greater by a factor of about 67. Research on turbulence has shown that the geometry of turbulence, jet shape, and eddy formation is nearly independent of the Reynolds number at values above 5000, except in boundary layers on surfaces.* Thus, it is probable that mixing performance in the prototype can be expected to be generally similar to that measured in the quarter-scale air-flow model.

Some studies have shown that turbulence levels many diameters downstream from the base of a jet may vary with a power of the Reynolds number. The exact power varies with conditions, but is usually in the range of 0.1 to 0.2. While it does not appear probable that such conditions apply in the lower plenum, they would be more likely to apply to flow through shield passages, or other areas where long flow distances are encountered. If applicable, such turbulence effects would result in greater mixing by turbulent diffusion in the prototype than in the model, the mixing effectiveness being increased by some factor between 1.4 and 2.4. It appears probable that a more exact value of this factor could be determined by taking model test data at several flow rates and extrapolating to prototype conditions. This work was not within the scope of the current project.

The temperature distribution of prototype coolant may be influenced by heat transfer to metal surfaces as well as by mixing. This effect could occur only in the shield passages, and in flow passing close to the pressure vessel. Heat transfer to the inlet jets would be negligible except for that occurring as the result of turbulent mixing of fluids of different temperatures.

* Townsend, A. A., The Structure of Turbulent Shear Flow, Cambridge University Press (1956).

RECOMMENDATIONS

If it should prove necessary to improve mixing, it is recommended that simple modifications of the flow baffle under the core be investigated. It is possible that plugging the holes into which inlet jets now impinge might substantially reduce peak concentrations now existing, with only minor changes in flow through the shield region, and with negligible change of flow distribution in the reactor core.

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