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DOE/ET/37240-76

COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Progress Report

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Principal Investigators

Neil E. Todreas - Tasks I and II
Michael W. Golay - Task III
Lothar Wolf - Task IV

Massachusetts Institute of Technology
Department of Nuclear Engineering
Cambridge, Massachusetts 02139

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A. Quarterly Progress Reports (Available from:
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151)

COO-2245-1	Period June 1, 1972 - November 30, 1972
COO-2245-2	Period December 1, 1972 - February 28, 1973
COO-2245-3	Period March 1, 1973 - May 31, 1973
COO-2245-6	Period June 1, 1973 - August 31, 1973
COO-2245-7	Period September 1, 1973 - November 30, 1973
COO-2245-8	Period December 1, 1973 - February 28, 1974
COO-2245-10	Period March 1, 1974 - May 31, 1974
COO-2245-13	Period June 1, 1974 - August 31, 1974
COO-2245-14	Period September 1, 1974 - November 30, 1974
COO-2245-15	Period December 1, 1974 - February 28, 1975
COO-2245-23	Period March 1, 1975 - May 31, 1975
COO-2245-25	Period June 1, 1975 - August 31, 1975
COO-2245-26	Period September 1, 1975 - November 30, 1975
COO-2245-28	Period December 1, 1975 - February 29, 1976
COO-2245-30	Period March 1, 1976 - May 31, 1976
COO-2245-31	Period June 1, 1976 - August 31, 1976
COO-2245-34	Period September 1, 1976 - November 30, 1976
COO-2245-38	Period December 1, 1976 - February 28, 1977
COO-2245-50	Period March 1, 1977 - May 31, 1977
COO-2245-53	Period June 1, 1977 - August 31, 1977
COO-2245-60	Period September 1, 1977 - November 30, 1977
COO-2245-63	Period December 1, 1977 - February 28, 1978
COO-2245-64	Period March 1, 1978 - May 31, 1978
COO-2245-65	Period June 1, 1978 - August 31, 1978
COO-2245-66	Period September 1, 1978 - November 30, 1978

COO-2245-69 Period December 1, 1978 - February 28, 1979
COO-2245-70 Period March 1, 1979 - May 31, 1979
COO-2245-71 Period June 1, 1979 - August 31, 1979
DOE/ET/37240-72 Period September 1, 1979 - November 30, 1979
DOE/ET/37240-75 Period December 1, 1979 - February 29, 1980
DOE/ET/37240-76 Period March 1, 1980 - May 31, 1980

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* Revised - See Section B.2

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COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

QUARTERLY PROGRESS REPORT

The work of this contract has been divided into the following Tasks:

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data

TASK IB: Experimental Bundle Water Mixing
Investigation

TASK IC: Experimental Bundle Peripheral
Velocity Measurements
(Laser Anemometer)

TASK ID: Analytic Model Development - Bundles

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

TASK IIB: Experimental Subchannel Water
Mixing Investigation

TASK IIC: Experimental Subchannel Local
Parameter Measurements
(Laser Anemometer)

TASK IID: Analytic Model Development-Subchannels

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

TASK IIIA: Analytical and Experimental Investigation
of Velocity and Temperature Fields

TASK IV: THEORETICAL DETERMINATION OF LOCAL TEMPERATURE FIELDS
IN LMFBR FUEL ROD BUNDLES

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

I.A Assessment of Available Data

I.B Experimental Bundle Water Investigations

- I.B.1 61 Pin Fuel Bundles - Turbulent Flow
- I.B.2 61 Pin Fuel Bundles - Laminar and
Transition Flow
- I.B.3 217 Pin Fuel Bundle
- I.B.4 61 Pin Blanket Bundles
- I.B.5 Shaved Wire 61 Pin Blanket Bundle
- I.B.6 37 Pin ($P/D=1.15$) Bundle
- I.B.7 Experimental Method for Flow Split
Determination
- I.B.8 Experimental Method for Pressure Drop
Determination
- I.B.9 Experimental Method for Mixing Parameter
Determination

I.C Experimental Bundle Peripheral Velocity
Measurements (Laser Anemometer)

I.D Analytic Model Development - Bundles

- I.D.1 Steady State ENERGY/SUPERENERGY
- I.D.2 Transient TRANSENERGY
- I.D.3 Models for Forced Convection Analysis
(Pressure Drop, Flow Split and Mixing)
- I.D.4 Models for Mixed Convection
 - I.D.4.1 Models for Mixed Convection - Subchannel
 - I.D.4.2 Models for Mixed Convection - Assembly
 - I.D.4.3 Models for Mixed Convection - Core
 - I.D.4.4 Predictors of Inception of Mixed Convection
- I.D.5 Determination of Shape Factors

TASK I. BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

I.A Assessment of Available Data

No work done on this task. This work was last reported in Progress Report COO-2245-72 dated September 1, 1979 - November 30, 1979.

I.B EXPERIMENTAL BUNDLE WATER INVESTIGATIONS

I.B.1 61 Pin Fuel Bundles - Turbulent Flow

(Paul Symolon)

Work on the 61 pin bundle in the turbulent flow regime has been completed. A topical report is being prepared for distribution shortly presenting the data and analysis.

I.B.2 61 Pin Fuel Bundles - Laminar and Transition Flow

(Paul Symolon)

Work on the 61 pin bundle in the laminar and transition flow regime has been completed. A topical report is being prepared for distribution shortly which presents the data and analysis.

I.B.3 217 Pin Fuel Bundle

(Paul Symolon)

During this quarter, the mixing data for the 217 pin bundle was reduced and analyzed. Figure 1 presents the values obtained for C_1 calibrated by SUPERENERGY-DRV-1 as a function of Reynolds Number for four injection depths. The 48 inch results were made with side pressure tap salt injection, while all of the other runs were made with injector rod salt injection. In all of these cases, the injection flowrate was calculated to equate the axial component of the injection velocity with the subchannel axial velocity to minimize the disturbance to the flow. The results are seen to vary with injection depth, but saturate to a constant value for the 36 and 48 inch injection runs for fully turbulent flow, $Re > 5,500$. Also shown is the value from the correlation of Chiu et al (Reference (1)) with an error bar of $\pm 25\%$ representing the spread of existing data about the correlation. Unlike the 61 pin bundle mixing test results, the shallow injection results are below, not above the deep injection data, but the variation with injection depth is not as large. (The fully turbulent results for all injection depths are within the error bar.) For this data, we would not expect injection effects to be as important since

our injection velocities are about 25% less than they were calculated to be because of a systematic error due to the flowmeter.

The mixing data was also reduced using the SUPERENERGY-DRV-2 code, which requires an input of two sets of data taken at the same Reynolds number but different axial levels. As found in Reference 2, the deep injection results from DRV-1 were better than any combination of injection depths using DRV-2.

The recommended value of C_{1L} for the 217 pin bundle is based on the deep injection results. For the fully turbulent regime the value for C_{1L} ($= \frac{C_1}{x_2} = \frac{.11}{1.04}$) is .106, which is above the value from the correlation by 10%. It seems reasonable that C_{1L} will increase with bundle size, since the effect of the restricted swirl flow due to the corner subchannel is small. The concept of reduced swirl flow in edge subchannels next to a corner subchannel was also presented in Reference 1. Two separate correlations were presented for C_{1L} . One was for edge to corner subchannel sweeping flow when the donor edge subchannel is next to a corner pin (valid for 7 and 19 pin bundles), and one for edge to edge subchannel sweeping flow when the donor edge subchannel is not adjacent to a corner pin (valid for 37 pin bundles, and larger). The correlation

for small bundles has the same calibration constants as the correlation for large bundles (there is no significant data base for 7 and 19 pin bundles). It differs only in subchannel centroid to centroid distance and relevant areas, which comes out of the physical modeling.

The two correlations are plotted in Figure 3.5 along with the old data points and one from the present analysis. The difference between the two correlations is small (well within the $\pm 25\%$ variation in data points). The new data point is above the correlation, but within the $\pm 25\%$ error bar. The variation may be attributed to errors in determination of C_{1L} , or to a small bundle size effect.

From the new data point obtained at MIT, we conclude that if any bundle size effect exists, it is small, and can be neglected with respect to errors in determination of C_{1L} .

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FIGURE 2

○	MIT Blanket	61 pin
⬡	MIT Fuel (Laser)	61 pin
◇	MIT Fuel (Salt)	61 pin
□	ANL - CT	91 pin
△	ANL - RAS	91 pin
▽	Cadarache	7 pin
⬠	MIT (salt)	217 pin

I.B.4 61 Pin Blanket Bundles

Work on these bundles was completed and reported in a series of topical reports by C. Chiu which are listed under B.1 Original Topical Reports and under C. Papers and Summaries.

I.B.5 Shaved Wire 61 Pin Blanket Bundle (Song Feng Wang)

Analyses of the experimental data are being prepared at this time. They will be issued as a topical report by the Fall period.

I.B.6 37-Pin ($P/D = 1.15$) Bundle
(Kevin Burns)

Reduction of the mixing data collected for the 37-Pin bundle is completed. Due to the breakdown of the floppy disk drive used to run the intermediate data processing programs, the data was reduced without a background calibration for correction for each mixing run. When performed, the calibration for correction shifts the probe readings to account for changes due to oxidation and temperature. The massbalance ratios (usually considered an indication of the validity of the data) which resulted were consistently greater than 1.0. Furthermore, the deviation of the massbalance from the ideal value of 1.0 increased with decreasing flow rate. Thus, only the following values for the turbulent mixing parameters are recommended with any confidence:

$$\epsilon_{1L}^* = 0.11$$

$$C_{1L} = 0.20$$

These values are within the error bars of the current turbulent sweeping flow correlation.

I.B.7 Experimental Method for Flow Split Determination
 (James T. Hawley)

The manual on the flow split method was completed in this quarter. It will be issued as Topical Report No. 80 entitled "The MIT Extraction Method for Measuring Average Subchannel Axial Velocities in Reactor Assemblies" by J. T. Hawley, C. Chiu and N. E. Todreas.

I.B.8 Experimental Method for Pressure Drop Determination
 (Kevin Burns)

This task was completed and reported in Topical Report No. 77 - "Laboratory Manual for Static Pressure Drop Experiments in LMFBR Wire Wrapped Rod Bundles". No work has been performed subsequently.

I.B.9 Experimental Method for Mixing Parameter Determination
 (Yee Ning Chan)

Topical Report No. 62 reported on these experimental methods. This report will be updated and reported in the next period.

I.C. EXPERIMENTAL BUNDLE PERIPHERAL VELOCITY MEASUREMENTS
 (Laser Anemometer)

No work is being done on this Task at present.

I.D ANALYTIC MODEL DEVELOPMENT - BUNDLES

I.D.1 Steady-State ENERGY-III

(Tom Greene)

The ENERGY codes [1,2] (ENERGY-I, II, and III) are a series of thermal-hydraulic computer codes designed to analyze single LMFBR wire-wrapped fuel assemblies subject to adiabatic boundary conditions at the hexagonal housing wall. These codes are based on a simplified model of the action of the wire-wrap in promoting lateral energy transport; the ENERGY model [1].

A number of improvements have been made to the ENERGY model since the release of the ENERGY codes. A revised version of the ENERGY-III code has been developed to include these improvements and to implement a number of improvements to the numerical solution scheme and to the input/output features of the code. The following features are included in the new version of the code:

- (i) The bundle-size independent mixing parameters ϵ_{1L}^* and C_{1L} have been introduced to the code. These mixing parameters replace ϵ^* and C used in the original code. The energy and momentum conservation equations have been reformulated to accept these parameters $(\epsilon_{1L}^*, C_{1L})$.

- (ii) The Hawley and Chiu [3] friction factor model has been included as an option.

This option allows calculation of the friction factors in laminar, transition and turbulent flows.

- (iii) A new matrix inversion technique has been included . This new inversion technique improves the computational efficiency of the mixed convection solution (energy, momentum, and continuity equations solved simultaneously).

- (iv) The forced convection solution of the ENERGY-I code and the mixed convection solution of the ENERGY-III code are combined as a single code hereafter known simply as the ENERGY-III code.

- (v) The ENERGY-II code has been deleted. The improved numerical solution of the ENERGY-III mixed convection option has made analysis of prototypical assemblies economically feasible without resorting to the more approximate solution of the ENERGY-II code (the ENERGY-II code neglects the convective terms in the axial momentum equation).

The new version of the code was compared with the experimental data reported by W-ARD [4] for their series 2 radial blanket heated tests. Figures 1-8 compare the forced and mixed convection options' predictions and the reported experimental data. A code manual describing the new code is being prepared for release as a topical report. The models used in both the mixed and forced convection solutions, as well as the numerical solution schemes employed, are described in Ref. [5].

References)

- (1) Khan, E. U. et al, "A Porous Body Model for Predicting Temperature Distributions in Wire-Wrapped Fuel and Blanket Assemblies for a LMFBR," COO-2245-16TR, MIT, March 1975.
- (2) Khan, E. U. et al, "Manual for ENERGY I, II, III Computer Programs," COO-2245-18TR, MIT, May 1975.
- (3) Hawley, J. T., "Hydraulic Studies of Liquid Metal Fast Breeder Reactor Subassemblies," S. M. Thesis, Dept. Nuclear Engineering, MIT, May 1980.
- (4) Memo CM-79-406, J. V. Yerace, "Transmittal of 15 Heated Tests (Run #2)," March 8, 1979 to members of LMFBR Thermal Hydraulic Working Group.
- (5) Greene, T. E., "Development and Evaluation of Techniques for Thermal-Hydraulic Analysis of LMFBR Fuel Assemblies," S. M. Thesis, Dept. Nuclear Eng'g, MIT, July 1980.

Figure 1 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 221 Level C

Figure 2 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 221 Level A

Figure 3 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 223 Level C

Figure 4 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 223 Level A

Figure 5 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 224 Level C

Figure 6 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 224 Level A

Figure 7 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 232 Level C

Figure 8 Comparison of ENERGY-III Predictions to W-ARD Experimental Data Test 232 Level A

I.D.2 Transient TRANSENERGY

(Tom Greene)

Descriptions of the TRANSENERGY-S and TRANSENERGY-M codes are being prepared and will appear as topical reports during the fall period.

I.D.3 Mixing Model for Forced Convection Analysis

(Kevin Burns)

A laminar/transition sweeping flow mixing model has been developed. The current turbulent mixing model was extended to low Reynolds number flows by assuming that the subchannel form pressure drop is the driving force for crossflow for all flow regimes. In addition, a parabolic subchannel velocity distribution is assumed. The laminar/transition model is based on a crossflow friction factor of the following form:

$$K_{ij} = kRe_b^m$$

where K_{ij} is the crossflow friction factor, Re_b is the bundle Reynolds number, and k and m are constants. The constant m is evaluated by assuming that the crossflow exhibits the same Reynolds number dependence as does the bundle average resultant (axial plus transverse) flow. The parameter k should be calibrated as a function of P/D . However it is taken as constant due to the lack of sufficient low Reynolds number mixing data available for calibration. The following low Reynolds number mixing correlations are recommended for Reynolds numbers less than the Reynolds number at which the laminar/transition and turbulent correlations yield the same value. For higher Reynolds numbers, the turbulent correlation [1] is recommended.

Interior to Interior Subchannels

$$\epsilon_{iL}^* = 0.0091 \left(\frac{A_r}{A_s} \right)^{0.5} Re_b^{0.35} \left(\frac{gap}{\eta} \right)^{-0.50} \left[\sin \theta \left(\frac{D_w}{De} \right) \left(1 - \frac{D_w}{2De} \right) \right] \frac{p^2}{A_s}$$

where:

$$gap = P - D$$

$$A_r = \left[\pi (D/2 + D_w)^2 - \frac{\pi D^2}{4} \right] / 6$$

$$A_s = \frac{\sqrt{3}}{4} P^2 - \frac{\pi D^2}{8} - \frac{\pi D_w^2}{8}$$

$$De = 4A_s / \left[\frac{\pi}{2} (D + D_w) \right]$$

$$\eta = P / \sqrt{3}$$

$$\sin \theta = \frac{\pi P}{\sqrt{(\pi P)^2 + H^2}}$$

Edge to Edge Subchannels

$$C_{1L} = 0.81 \left(\frac{A_r}{A_s} \right)^{0.5} Re_b^{0.35} \left(\frac{gap}{\eta} \right)^{0.35} \left[\sin \theta \left(\frac{D_w}{De} \right) \left(1 - \frac{D_w}{2De} \right) \right]$$

where:

$$gap = P - D$$

$$A_r = \left[\pi (D/2 + D_w^2) - \frac{\pi D^2}{4} \right] / 4$$

$$A_s = P(D/2 + D_w) - \frac{\pi D^2}{8} - \frac{\pi D_w^2}{8}$$

$$De = 4A_s / \left[P + \frac{\pi}{2} (D + D_w) \right]$$

$$\eta = P$$

$$\sin\theta = \frac{\pi P}{\sqrt{(\pi P)^2 + H^2}}$$

Reference:

- [1] C. Chiu, W. M. Rohsenow and N. E. Todreas, "Turbulent Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies", COO-2245-55TR, Dept. of Nuclear Engineering, M.I.T., Rev. 1, October 1978.

I.D.4 Models for Mixed Convection

I.D.4.1 Models for Mixed Convection - Subchannels

(Song Feng Wang)

Work on this task was completed and reported in topical report COO-2245-73TR which is listed in the front of this report.

I.D.4.2 Models for Mixed Convection - Assembly

(Song Feng Wang)

During this quarter, the fabrication of a test loop for mixed convection experiments has been started; the conversion of the BODYFIT code from IBM system to MULTICS system has been started, and the experimental methods pertinent to low velocity measurements has been reviewed.

The test loop, as shown in Figure 1, includes pumps, flowmeters, filter, driving tank, test section, inlet and outlet plenums, and thermometers at various locations. The flow through the test section can be arranged either in-upward or downward direction by various controlling values. A driving tank is included to eliminate the flow disturbance caused by pump vibrations

and provide, through gravity head; a stable flow to the test section. The pumps can be isolated from the rest of the loop. Natural circulation within the close-loop formed by the test section and the driving tank can be achieved provided a cooling coil is installed in the driving tank to remove the heat and provide the necessary difference in thermal head.

The test section contains sixteen (4x4) electrically heated rods arranged in square lattice. The power of the rods is uniformly distributed over the heated length of 36 inches and rated at maximum power of 2kw (at 200 volts) per rod. The square lattice was chosen so that the flow distribution in the interior subchannels can be detected.

The rods are fixed to the top of the outlet plenum via two tie plates and allowed to expand freely at the bottom of the test section. In this manner, the thermal stresses within the rods are minimized and hence eliminate any rod bowing problem due to the rod support system.

The distance between the rods is maintained by three spacers located at the middle and two ends of the test section. The original BNWL design of the spacer was adopted. It is composed of short pieces of stainless steel thin wall tubing which is tied between the rods and between the rods and the wall to serve as the spacer. The side

view and the top view of the test section are shown in Figure 2a and 2b, respectively.

The flow housing of the test section is made by four pieces of stainless steel plates. On the front and the back faces of the housing, there are a total of three pairs of window to facilitate the velocity measurement. These three pairs of window are located near the middle and each end of the test section corresponding to the inlet, developing, and fully-developed (if any) flow conditions. Two moving probes, penetrating from the left and the right faces, are installed to measure the pressure and temperature distributions. The flow pattern will be made visible by either injecting the dye into the flow stream or by generating hydrogen bubbles from those moving probes.

The flow visualization technique will be adopted as a first try to measure the velocity distributions mainly because the conventional Pitot tube tends to disturb the flow and is not sensitive at low flow rate; the hot-wire anemometer is easily damaged from the contamination problem; the highly advanced LDA methods require sophisticated data acquisition system. In addition, none of these methods gives a direct visualization of the flow pattern. However, if the flow visualization techniques failed to give quantitative measurements of the flow distributions, other methods like LDA will be pursued.

Figure 1. Test Loop

Figure 2(a). Side View of the Test Section

Figure 2(b). Top View of the Test Section

I.D.4.3 Models for Mixed Convection - Core

(Paul Symolon)

Results of this work were reported earlier in progress report DOE/ET/37240-72. Work is continuing in this area and additional results will be presented in the near future.

I.D.4.4 Predictors of Inception of Mixed Convection

(Tom Greene)

When considering the use of a forced convection code for predicting the temperature fields within a heated rod bundle, the importance of mixed convection must be ascertained. Khan [1] proposed a modified Grashof number (Gr^*) as a predictor of inception of mixed convection.

Gr^* is defined as:

$$Gr^* \equiv \frac{Gr^+}{f Rey^2} \qquad Gr^+ \equiv \frac{g\beta De^3 (\Delta T)}{\nu^2}$$

where:

Gr^* = Modified Grashof Number

Gr^+ = Grashof Number based on a lateral temperature difference

f = friction factor

Rey = Reynolds Number

A constant value of $Gr^* = .025$ was proposed [1] as a criterion for inception of mixed convection.

Comparisons [2] of forced convection code predictions to experimental data were made for a number of cases where Gr^* predicted that mixed convection was negligible (i.e. $Gr^* < 0.025$). The results indicated that mixed convection was present in several of the cases.

This discrepancy motivated a study of Gr^* as a predictor of mixed convection.

A calibration of Gr^* was done for the case of a prototypical LMFBR blanket assembly. A criterion of a 5°F difference between the solutions of the forced and mixed convection options of the ENERGY-III code was used. The results are shown in Figure 1. It was found that the critical value of Gr^* for inception of mixed convection was a function of at least Reynolds Number and radial power skew.

A second predictor of mixed convection, ϕ_β , was proposed. ϕ_β was derived from consideration of the relative importance of the transverse energy transport due to buoyancy-induced crossflow in comparison to the transverse energy transport due to turbulent interchange, wire-wrap mixing, and conduction heat transfer. A ratio of the heat flows was made and the inequality taken as:

$$\frac{\dot{q}_B}{\dot{q}_M + \dot{q}_C} \ll 1$$

a definition of negligible mixed convection,
where:

$$\dot{q}_B = \text{transverse energy flow due to buoyancy cross-} \\ \text{flow}$$

$\dot{q}_M$ = transverse energy flow due to the combined effects of wire-wrap mixing and turbulent interchange.

$\dot{q}_C$ = transverse energy flow due to conduction heat transfer.

After introducing the transverse momentum equation and making a number of simplifications, the quantity ϕ_β was defined as

$$\phi_\beta \equiv \frac{\eta [g\beta L\Delta T(P/D-1)]}{(\epsilon_{HN1}/\lambda_{L1} + SF\alpha)}$$

where

η = centroid distance between adjacent subchannels

g = acceleration of gravity

β = thermal expansion coefficient

ΔT = lateral temperature difference

L = assembly heated length

P/D = rod pitch to diameter ratio

$\epsilon_{HN1}/\lambda_{L1}$ = combined turbulent and wire-wrap mixing coefficient based on gap width $(P-D)$

SF = conduction shape factor based on gap width $(P-D)$

α = thermal diffusivity of coolant

A calibration of ϕ_β as a predictor of mixed convection showed that it must be correlated as a function of at least Reynolds number and radial power skew. Figure 2 presents the calibration curve for ϕ_β for the same case as Figure 1 for Gr^* . The 5°F criterion discussed earlier was used in the calculations which led to Figure 2.

A relation between ϕ_β and Gr^* for high Reynolds number was found:

$$\phi_\beta = \left(\frac{\eta}{De_1}\right) \left[\left(\frac{L}{De_1}\right)(P/D-1)\right]^{1/2} \frac{\sqrt{f}}{\epsilon_{1L}^*} \sqrt{Gr^*}$$

where

f = friction factor

ϵ_{1L}^* = dimensionless, bundle-size independent
mixing parameter

De_1 = interior subchannel hydraulic diameter

The principle advantage of ϕ_β is that it considers the effects of wire wrap mixing, turbulent interchange and thermal conduction and buoyancy. Gr^* considers only the relative effects of buoyancy and axial friction effects. The major differences should appear at low Reynolds numbers.

A complete discussion of Gr^* and ϕ_β is available in [2]. It will be released as a Topical Report in the near future.

References

- (1) Khan, E. U. et al, "A Porous Body Model for Predicting Temperature Distributions in Wire-Wrapped Fuel and Blanket Assemblies for a LMFBR," COO-2245-16TR, MIT, March 1975.
- (2) Greene, T. E., "Development and Evaluation of Techniques for Thermal-Hydraulic Analysis of Liquid Metal-Cooled Fast Breeder Reactor Assemblies," S. M. Thesis, Dept. Nuclear Eng'g, MIT, July 1980.

Figure 2.

I.D.5 Shape Factors for Transverse Conduction in Rod
 Bundles

(Tom Greene)

No work has been performed in this area during the present quarter. The latest report on this topic was in the quarterly progress report number COO-2245-72.

IV. THEORETICAL DETERMINATION OF LOCAL TEMPERATURE FIELDS IN LMFBR FUEL ROD BUNDLES

Wire-Wrapped Rod Bundle Heat Transfer Analysis

(Chung-Nin Channy Wong)

Introduction

Previous progress reports [1,2], showed that the computer code Flow3DT had been used to analyze several simple pipe flow problems with various kinds of inlet conditions. Results from these calculations had been compared with results from other literature citations. Their agreement was remarkably good. Next, the ongoing work can be divided into two different areas. The first one is to implement the energy equation into the code. Since our aim is to apply the Flow3DT code to calculate the temperature fields in the wire-wrapped rod bundle geometry, the code should be able to solve the energy equation as well as the equations of motion. The second task is to extend the capability of the code to handle some problems of complicated geometry. Our intention is to test the code against several well-understood complicated boundary-value problems before proceeding further into the wire-wrapped rod bundle geometry.

As of the end of this quarter of the year, the work on the energy equation has not been completed. Therefore, the rest of this report will be devoted to a discussion about the progress on solving fluid flow problems with complicated geometry.

Fluid Flow Problems with Complicated Geometry

The work in this area can be separated into two different kinds of problems. The first one is to analyze the fluid flow in the bare rod bundle. The second one is to study the swirling flow in a concentric annulus with a twisted tape.

For the bare rod bundle flow problem, our concentration is restricted to a small fluid cell, as defined in Figure 1. Each assembly consists of a number of these hexagonal cells with the fuel element located at the center of each cell. There are three kinds of cells in each assembly. They are interior, corner and edge cells. Because of the symmetry, each interior cell will be treated as an isolated cell. This implies that the outer boundary condition of each cell is adiabatic and has zero shear stress. Hence, the problem is simplified and economically feasible to analyze. Without power skew in the assembly, and if the interior cell is far away from the wall, this assumption is satisfactory.

The geometry of the example problem that has been analyzed is:

$$P/D = 1.24$$

The flow condition is:

$$Re = 200$$

$$V_r = 0, V_\theta = 0, V_z = \text{constant for inlet velocities}$$

Figure 2 shows the axial distribution of the mean pressure of the interior cell. The friction factor which relates to the gradient of the curve is almost constant throughout the channel except the region where the entrance effect still dominates. It is known that in fully developed laminar flow situations, the product of the friction factor and the Reynolds number is equal to a constant. The calculated value of this example problem is 22.308, which has an error of -7% if compared to Meyder or Rehme's results [3,4]. Figure 3a shows the development of the axial velocity profile along the line AA' as shown in the diagram. Figure 3b shows the plot of the maximum velocity vs axial length. The maximum axial velocity in this problem is located at the vertex of the hexagonal cells. However, there is some disagreement between this velocity profile and the result from Meyder's calculation. The percentage of error in our calculation is about 30%. This difference can be explained by the following factors.

1. The meshes are too coarse in this calculation. A coarser mesh has been used due to the limited storage space and computing time. But such a coarse mesh may generate a large truncation error which will lead to a wrong answer. Modification of the code is needed to allow finer mesh.

2. The outer boundary condition is not set right. Since the fluid cells at the outer boundary have irregular geometry, interpolation is needed to specify the boundary condition for these cells. Incorrect specification of the boundary condition may lead to instability or inaccuracy.

3. The equilibrium state has not been achieved yet. Molecular diffusion is a slow process. A long time is required to reach steady state. It is possible that our solution has not reached steady state yet. Moreover, the entrance effect could also be a factor.

4. A numerical error exists in the code. More debugging will be done to improve the code. Additional investigation is underway to insure the code against inaccuracy and instability. Progress will be reported in the next quarterly report.

The second problem is to analyze the flow in a concentric annulus with a twisted tape. To model the twisted tape, a discrete rotating flow blockage is

introduced. Near the blockage, fluid will be restricted to flow in the traverse direction. Thus, a swirling flow will occur in the duct. Figure 4 shows the azimuth and axial velocity profile of two rows of fluid cells A,B adjacent to each other. Obviously, as shown in this Figure, velocities at the location of the blockage are zero. If the two curves are compared, some similarity is found between the pattern of both curves. This implies that it is not necessary to analyze fully one lead length of the twisted tape. A substantial reduction will be realized in the amount of computing time and storage space. A small recirculation has been observed at the location of the step blockage. This may be caused by numerical instability. A thorough check on the programming of the code is underway to eliminate this instability.

Future Work

An energy equation is being implemented into the code. It will be tested against several problems such as simple pipe flow and bare rod bundle geometry. Further improvement of the hydraulic part of the code including dissolving all the problems discussed in the last section will be done. Finally, the wire-wrapped rod bundle geometry will be analyzed after all the problems have been solved.

References

1. C-N Wong, "Cooling Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients", Progress Report, Sept. 1979-Nov. 1979, MIT Report COO-2245-72.
2. C-N Wong, "Cooling Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients", Progress Report, Dec. 1979 - Feb. 1980, MIT Report COO-2245-75.
3. R. Meyder, "Solving the Conservation Equations in Fuel Rod Bundles Exposed to Parallel Flow by Means of Curvilinear-Orthogonal Coordinates", J. of Comput. Phy., No. 17, P 53-67 (1975).
4. K. Rehme, "Laminarströmung in Stabbündeln", Chem. - Ing - Tech. No. 43, p 962-966 (1971).

Fig. 1 Schematic Diagram for Fuel Assemblies

Fig. 2 Axial Distribution of the Mean Total Pressure for the Interior Cell of Rod Bundle with $Re=200$, $P/D=1.24$

Fig.3 Axial Velocity Profile of Interior Cell of Rod Bundle
at $Re=200$, $P/D=1.24$

Fig. 4 Velocity Distribution of a Concentric Annulus with Discrete Rotating Flow Blockage $H/d_0 = 4$, $Re=200$, $\Delta\theta = 0.1963$ at $r/d_0=0.7976$

THREE-DIMENSIONAL STEADY ISOTHERMAL FLOWS

(Robert W. Sawdye)

During this three month period, work has proceeded on the construction of the major components of the experimental apparatus. The major plexiglas pieces for the test section have been created and are ready for assembly. The water tank, which will surround the test section, has been constructed; however, further work is required to ensure that the tank remains leakproof for the duration of the experimental program.

The repair of the turbulence processor has been completed. Thus, the two lasers and their associated optics are in working condition and have been assembled on a table and an optical bench around the water tank. Further work is required to permanently mount these components to ensure that they do not move at any time during the measurement period. Also, there must be maintained some flexibility in the mounts due to the alignments that will have to be made when all of the components are assembled and measurements can begin. The milling table has been fitted with an overhanging beam which will support the test section within the water tank. This beam will have to be made more rigid to avoid vibration of the test section.

No further efforts have been made to calculate the flow within the test section using TEMPEST or any other computer code. It is planned that R. W. Sawdye will spend several of the next few months at the Battelle Pacific Northwest Laboratories working with Dr. D. S. Trent on TEMPEST development to become more familiar with the code.