COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Progress Report

Principal Investigators

Neil E. Todreas

Michael W. Golay

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

December 1, 1975 - February 29, 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared for the U.S. Energy Research and Development
Administration under Contract No. AT(11-1)-2245

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

24

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Reports Issued Under This Contract

A. Quarterly Progress Reports

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 31, 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

Reports Issued Under This Contract

B. Topical Reports

E. Khan and N. Todreas, "A Review of Recent Analytical and Experimental Studies Applicable to LMFBR Fuel and Blanket Assembly Design," COO-2245-4TR, MIT, Sept. 1973.

E. Khan, W. Rohsenow, A. Sonin and N. Todreas, "A Simplified Approach for Predicting Temperature Distribution in Wire Wrapped Assemblies," COO-2245-5TR, MIT, September 1973.

T. Eaton and N. Todreas, "Instrumentation Methods for Interchannel Coolant Mixing Studies in Wire-Wrap Spaced Nuclear Fuel Assemblies," COO-2245-9TR, MIT, June 1974.

Y. B. Chen, K. Ip, N. E. Todreas, "Velocity Measurements in Edge Subchannels of Wire Wrapped LMFBR Fuel Assemblies," COO-2245-11TR, MIT, September 1974.

E. Khan, N. Todreas, W. Rohsenow, A. A. Sonin, "Analysis of Mixing Data Relevant to Wire-Wrapped Fuel Assembly Thermal-Hydraulic Design," COO-2245-12TR, MIT, Sept. 1974.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distributions in Wire Wrapped Fuel and Blanket Assemblies of a LMFBR," COO-2245-16TR, MIT, March 1975.

E. Khan, W. M. Rohsenow, A. Sonin, N. Todreas, "Input Parameters to the ENERGY Code (To be used with the ENERGY Code Manual) COO-2245-17TR, MIT, May 1975.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "Manual for ENERGY Codes I, II, III," COO-2245-18TR, MIT, May 1975.

P. Carajilescov and N. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle," COO-2245-19TR.

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer," COO-2245-20TR, MIT, May 1975.

F. Carre and N. Todreas, "Development of Input Data to Energy Code for Analysis of Reactor Fuel Bundles," COO-2245-21TR, MIT, May, 1975.

Reports Issued Under This Contract

B. Topical Reports, Continued

H. Ninokata and N. E. Todreas, "Turbulent Momentum Exchange Coefficients for Reactor Fuel Bundle Analysis," COO-2245-22TR, MIT, June 1975.

R. Anoba and N. Todreas, "Coolant Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients," COO-2245-24TR, MIT, August, 1975.

B. Bosy, "Fabrication Details for Wire Wrapped Fuel Assembly Components, COO-2245-27 TR, MIT, Nov. 1975.

Reports Issued Under This Contract

C. Papers and Summaries

Yi Bin Chen, Ka-Lam Ip, Neil E. Todreas, "Velocity Measurements in Edge Channels of Wire-Wrapped LMFBR Fuel Assemblies," American Nuclear Society Transactions. Vol. 19, 1974, pp. 323-324.

P. Carajilescov, N. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Sub-Channel of a Bare Rod Bundle," accepted for the ASME Winter Annual Meeting, Nov. 1975 (Included as Appendix to Quarterly Progress Report COO-2245-15).

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Fuel Rod Assemblies," Nuclear Engineering and Design, 35 (1975) 1-12.

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Inter-assembly Heat Transfer," Submitted to Nuclear Engineering and Design (included as Appendix to Quarterly Progress Report COO-2245-23).

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Rod Assemblies Operating in Combined Forced and Free Convection," Nuclear Engineering and Design, 35 (1975) 199-211.

Ralph G. Bennett and Michael W. Golay, "Development of an Optical Method for Measurement of Temperature Fluctuations in Turbulent Flows," American Nuclear Society Transactions. Vol. 22, 1975, p. 581.

B. Chen and N. Todreas, " "Prediction of the Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer" Nuclear Engineering and Design 35 (1975) 423-440, North Holland Publishing Co.

COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

Quarterly Progress Report

December 1, 1975 - February 29, 1976

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

Figures, Tables and References are grouped for each of the three
tasks at the end of the writeup of each task.

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

Task IA Assessment of Available Data (Kerry Basehore)

Introduction

During this quarter, work began on the assessment of limited amounts of world's data, including comparison with predictions of the MIT thermal hydraulic code SUPERENERGY. The goals of this work as they exist now are (1) to reassess older data using new information to discover possible effects on code prediction and (2) to assess and compare new data.

Reassessment of ORNL FFM-2A Bundle Data

The ORNL 19 pin Fuel Failure Mockup Bundle 2A (FFM-2A) Data⁽¹⁾ contributes a sizable portion of the data used in determination of the empirical correlations ϵ^* and C for the SUPERENERGY, ENERGY series of codes. Recently it was speculated that due to the FFM-2A bundle geometry a skewed flow distribution may exist at the entrance of the electrically heated zone. As can be seen in Figure 1-2 a 90° change in flow direction exists 16 inches (40.64 cm) before the heated zone causing a flow maldistribution. It is possible that the corresponding flow transition region may overlap the heated section. Flow would then be greater on the 1-6 bundle side (see Fig. I-1) than anticipated by a code using the flow model of equal pressure drops for each subchannel and less than anticipated on the 3-4 side (see Fig. I-1). Preliminary work done (Figures I-3 and I-4) using predictions from COBRA

III and SUPERENERGY with the equal-pressure-drop-across-the-bundle flow condition indicated overprediction of temperature by the codes on the 1-6 bundle side and under-prediction on the 3-4 bundle side as expected.

Personal communication with J. Wantland of ORNL confirms that ORNL did indeed do flow tests to check for flow maldistribution. The results of the tests indicates that no detectable flow maldistribution yielding an overall affect on end of bundle temperature distribution existed. Thus, until some future date when new experimental information is provided, the data-code mixmatch must otherwise be explained. A plausible explanation is the distortion of normal geometry which occurs when pins are heated. This phenomena is one we intend to seriously consider in future modeling efforts.

Assessment of ANL XX07 in Core Instrumented Test Bundle

The ANL XX07 Bundle offers an excellent opportunity to check the SUPERENERGY code against in core data. With this in mind preliminary data acquisition and reduction, particularly of Test G data began this quarter to enable comparison with SUPERENERGY predictions early in the upcoming quarter.

TASK I.B.1: 61-Pin Fuel Bundle Experiments (Alan S. Hanson)

Further work on modifications to the ENERGY thermal-hydraulic analysis computer code was accomplished during this quarter in order to produce a version which could model salt tracer experiments. A new subroutine to plot the computational results in an hexagonal grid pattern was written to replace the previous output lists. This method of display greatly improves the readability of output and makes possible a direct comparison with experimental bundle results.

A parametric study was made using the ENERGY code to determine the best way to use this program to analyze salt data. To simplify this study it was assumed that the eddy diffusivity terms for interior and edge regions were the same so that only two constants, ϵ and C , remain. The effect of C , which describes the swirl velocity is illustrated in Figure I-5. In this figure the salt concentration is plotted for each subchannel around the circumference of the bundle in a case of turbulent flow with an initial salt concentration of 0.48 g-salt/lbm-water in subchannel #2. For a fixed value of $\epsilon_H = 0.020$, C was varied from 0.11 to 0.19. The resulting curves show two basic characteristics as C is increased; first the peak of the distribution moves further around the circumference and second the magnitude of the peak decreases. It is the location of the peak on these curves which is the key determining a value of C from experimental data. In Figure I-6 a constant

value of 0.19 was taken for C and ϵ_H was varied from 0.005 to 0.030. The resulting curves indicate that the location of the peak concentration remains fixed but that the magnitude of the peak decreases substantially as ϵ_H is increased. Thus the magnitude of the concentration curves can be used to find ϵ_H from experimental data.

Figures I-7 and I-8 show the superposition of MIT mixing data onto the parametric curves of Figures 1 and 2. The lower curves are raw data with a 65% mass balance; when this data is adjusted uniformly to 100%, the upper curves result. Thus it appears that for this experiment C is about 0.19 and ϵ_H is about 0.025. Work is continuing to examine more of the MIT mixing data in this manner. Interior experiments are also being investigated. Some slight further changes to ENERGY are required to check laminar data.

Also during this quarter a manual describing the mixing data reduction procedure was written to document the method for future experimenters.

TASK IB.2: Experimental Bundle Water Mixing Investigation

Repeat of Laminar and Transition Flow - 61 Pin Fuel Mixing
Experiments (Stuart Glazer)

During the current quarter, work continued on the development of the 61 pin fuel bundle and all associated equipment required for flow mixing tests. Fabrication of the flow separator device, described in the January 1976 progress report, COO-2245-26, was completed. The device has since been assembled and mounted at the exit plane of the 61 pin bundle.

Experience gained in the design of the flow separator for the fuel bundle was passed onto C. Chiu for the purpose of designing a similar device for the 61 pin blanket bundle assembly.

Mixing tests previously performed by A. Hanson with the 61 pin fuel bundle terminated in bundle disassembly and short term storage of the pins, probes, and electronic hardware. Recent inspection of this equipment disclosed breakage of the wire wrap on approximately 26 of the 61 pins. During the current quarter, the wire wrapping device designated by B. Bosy, described in the document "Fabrication Details for Wire Wrapped Fuel Assembly Components", COO-2245-27TR, dated 11/75, was modified to permit wrapping of .25" OD simulated fuel pins with a 12 inch lead length. As a result, all fuel pins with broken wire wraps were rewrapped.

S. Glazer
Continued

Probes built previously by A. Hanson were determined to be unreliable due to their age. Design and fabrication of 125 electrical conductivity sensors was initiated and will be completed shortly. The new probes are slightly different from those used by A. Hanson in several respects. Since the probes need only fit within clearly defined subchannels in the flow separator, the diameters of the sensor casings have been increased significantly but will still fit into the subchannels. The increased casing diameter permitted the use of special thin wall heat shrinkable tubing as insulation over the soldered joint between the platinum electrode wires and copper lead wires, as opposed to scotch tape used in the previous probes. Special waterproof cement was applied to both ends of the probes to provide watertight seals. Platinization of the electrodes is planned shortly. Mounting fixtures to hold all probes in the appropriate subchannels have been designed, fabricated, and mounted on the flow separator.

Inaccuracies in saline solution injection at low flowrates were previously cited as a possible reason for very poor mass balances experienced by A. Hanson in low Reynolds number laminar mixing tests. To eliminate this problem in all future mixing tests performed at MIT, a positive displacement pump with an automatic pump speed controller was purchased. This pump can produce saline solution flowrates over the entire range required for all laminar and turbulent conditions.

In the next quarter, the electrical conductivity sensors will be completed and the data acquisition equipment built by A. Hanson will be retested. Mixing tests will be performed on the 61 pin fuel bundle in the low turbulent and throughout the laminar flow regime.

IB.3 217 Pin Fuel Mixing Experiments (S. Glazer)

No modification of the 217 pin fuel bundle received from HEDL was performed during the current quarter.

As a result of the LMFBR Rod Bundle Working Group Meeting, held at Westinghouse Advanced Reactors Division from 12/9/75 to 12/10/75, MIT was made aware of plans to perform natural circulation sodium heat transfer tests at HEDL in the next quarter. Preliminary investigation has disclosed that the currently planned flowrate and power test conditions can potentially yield most mixing data required for calibration of the ENERGY and SUPERENERGY computer codes. MIT is currently in the process of evaluating additional tests, and will shortly make recommendations to ARD and HEDL as to additional test flow and power conditions which would yield all mixing data required. Recommendations have already been transmitted to ARD and HEDL advising the placement of additional thermocouples in the test hardware. If it is concluded that these heat transfer tests with this HEDL bundle are useful in place of mixing tests, we will design the MIT 217 pin tests to obtain only hydraulic test data (flow split in steady state and transients). This

S. Glazer

hydraulic data is necessary to allow adequate interpretation of heat transfer or mixing data for code calibrations.

Pretest predictions of coolant temperatures under 2 uniquely identified series of flow and power conditions are currently being done with the ENERGY and SUPERENERGY computer codes. Comparison with similar outputs from THI-3D and actual test results will permit further evaluation of the accuracy of the ENERGY model approach. As a result of these comparisons, a minor error has been isolated in the code SUPERENERGY. The error only affects code predictions under conditions of very low flowrates, not encountered in normal reactor operations. The error has been corrected in a new experimental version of SUPERENERGY, now in use at MIT.

In the next quarter, after the 61 pin fuel bundle mixing tests have been run, physical modification of the 217 pin fuel bundle received from HEDL will be initiated. Among specific tasks planned are design and fabrication of a flow separator device, and purchase of pressure measurement instrumentation. Design and fabrication will be initiated on the computerized real time data acquisition system and a flow control valve, to permit examination of flow behavior during transient events.

Task IB.4 61 Pin Blanket Bundle Experiment - (Chong Chiu)

Previous work on collecting mixing data for analysis by the ENERGY computer code and pressure drop data for analysis of the flow characteristics on 61 pin blanket bundle by Carl H. Oosterman (refer to quarterly progress report COO-2245-14) shows some discrepancies on the obtained data. During this quarter, an extension to Oosterman's work is planned. In addition, repetition of his work with some improvement on the bundle specifications is prepared.

1.1 Repetition of Previous Work

Elimination of discrepancies on mixing and pressure data obtained by Oosterman requires a repetition of previous work. A general survey on the causes of erratic data has been made in this quarter. The major causes are listed as follows:

- 1) Low concentration calibration curve is uncertain,
- 2) Specifications of bundle housing is off from those of design. The actual specifications measured by EPL technicians and design specifications are shown in Figures I-9 and I-10.

C. Chiu (cont)

This specification uncertainty will cause errors on circumferential pressure data and mixing data.

During the next quarter, modifications on the bundle specifications will be initiated first in order to proceed with the measurements on this bundle.

1.2 Future Extension to Previous Work on 61 Pin Blanket Bundle

In order to analyze the experimental data by computer code ENERGY, the following data is needed besides the mixing data which has already been obtained (repetition on this part will be performed early next quarter).

- 1) Flow split at the exit of the bundle - to provide information to analyze the flow split between internal region and peripheral region. (flow split used as an input parameter in ENERGY code.)
- 2) Axial and transverse velocities in the edge channel - to evaluate the input parameter C (refer to page 8, topical report (COO-2245-16TR) for the definition of C).
- 3) Transient flow test - to verify mixing predictions by a transient version of the code SUPERENERGY.

Reliable flow split and mixing data are supposed to be obtained using flow separator (refer to progress report COO-2245-26) designed by Stuart Glazer. The design drawings of flow separator for this bundle have been done in this quarter. Fabrication of the flow

C. Chiu (cont)

separator is going to be accomplished in the early beginning of next quarter.

During next quarter, flow split experiment and edge subchannel experiments on LDA will be initiated as long as there is sufficient time to do so after modification on the bundle geometry and repetition of Oosterman's work.

1.3 Experiments on 61-pin Blanket (Alternate Wrap) Bundle

The wire wrap blanket bundle with alternate rows of rods wrapped in opposite directions has a characteristic of larger cross-assembly flow. It is believed this feature will help to flatten the blanket temperature profile. Currently, identified goals of 61 pin blanket (Alternatwrap) bundle test include the determination of pressure, flow split, subchannel velocities and mixing data in the turbulent, transition and laminar flow regimes. An option of flow transient test is maintained to verify mixing prediction by a transient version of the code SUPERENERGY. An evaluation of this type of blanket bundle in LMFBR mixing performance is the final purpose of a series of tests mentioned earlier through the code which will be developed in the future.

Fabrication of Alternat wrapped blanket fuel pins will be initiated in the next quarter. The general picture of the Alternat wrapped bundle is shown in Figure I-11.

The experiment on alternate wire wrap bundles is scheduled to be initiated at the end of next quarter. The first step of the experiment is to obtain the mixing data through salt injection techniques. Five injection rods are put inside the bundle. Two directions of salt injection for each rod is achieved by drilling two more holes at the bottom of the injection guide tubes. This provides two ways which corresponding to two injection directions to locate the injection holes. This feature can be shown on the following page in figure I-12.

The locations of injection rods and injection directions are chosen to show different flow characteristics inside the bundle. Figure I-13 illustrates the locations and injection directions of injection rods and the related flow patterns inside the bundle.

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

No work was performed this quarter - LDS unit is being used in Task III.

Task ID Analytic Model Development - Bundles (Kerry Basehore)

The SUPERENERGY, thermal hydraulic Code uses a critical modified Grashof number Gr_C^* to determine when buoyancy effects become important. Previously it was up to the code user to determine whether his input data fell below this criterion and was therefore acceptable for use in SUPERENERGY. One of several publications by Ehsan Khan could have been used for this purpose. During this quarter, however, it was found that several inconsistencies in the form of typographical errors and non-specific parameter definitions exist in these publications. Thus it was decided to formulate a small program for the calculation of Gr^* and eventually add it to SUPERENERGY thereby eliminating the problem. The program is finished and will be entered into SUPERENERGY during the code cleanup phase starting next quarter. Errata sheets for the various publications in which Gr^* inconsistencies occur will be sent out next quarter, also.

Included in Table 1 is a summary of code capabilities of ENERGY I, II & III and SUPERENERGY. A similar list was sent to Westinghouse for addition to their summary compilation.

TABLE 1

SUMMARY OF CAPABILITIES OF SUPERENERGY AND ENERGY FOR WIRE WRAPPED ASSEMBLIES

CODE	GEOMETRY							
	MAX NUMBER OF RODS	P/D	CHANNEL SHAPE	GAP WIDTH	WIRE WRAP PITCH	MAX. NO. OF FLOW CHANNELS	MAX. NO. OF AXIAL STEPS	SPECIAL EDGE CHANNEL TREATMENT
SUPERENERGY	NO LIMIT	NO LIMIT ⁽¹⁾	STANDARD	NO LIMIT	YES	NO LIMIT	NO LIMIT	YES
ENERGY I	NO LIMIT	NO LIMIT ⁽¹⁾	STANDARD	NO LIMIT	NO	NO LIMIT	NO LIMIT	YES
ENERGY II	NO LIMIT	NO LIMIT ⁽¹⁾	STANDARD	NO LIMIT	YES	NO LIMIT	NO LIMIT	YES
ENERGY III	NO LIMIT	NO LIMIT ⁽¹⁾	STANDARD	NO LIMIT	YES	NO LIMIT	NO LIMIT	YES

CODE	FLOW PARAMETERS					
	PRESSURE DROP	REYNOLDS NUMBER LIMIT	FRICTION FACTOR	BUOYANCY	COOLANT PROPERTY VARIATIONS	SUBCHANNEL FLOW AREA VARIATION CAUSED BY WIRE WRAP
SUPERENERGY	YES ⁽²⁾	FORCED CONVECTION ONLY ⁽³⁾	YES	NO	YES	NO
ENERGY I	NO	FORCED CONVECTION ONLY ⁽³⁾	NO	NO	YES	NO
ENERGY II	YES	> 1000 ⁽⁴⁾	YES	YES	YES	NO
ENERGY III	YES	> 1000 ⁽⁴⁾	YES	YES	YES	NO

CODE	MASS AND THERMAL ENERGY TRANSPORT MECHANISMS				
	TURBULENT INTENSITY CAN REPRESENT	INTENSITY CAN BE ZERO	CROSS FLOW DIVERSION	FLOW SWEEPING	GROSS FLOW SWIRL
SUPERENERGY	MODELED AS A DIMENSIONLESS EDDY DIFFUSIVITY ϵ^* WHICH CAN BE EMPIRICALLY DETERMINED				YES
ENERGY I					YES
ENERGY II					YES
ENERGY III					YES

(1) Provided a valid dimensionless eddy diffusivity ϵ^* can be provided covering the range of interest.

(2) Used in flow split calculation.

(3) Really a Gr^* limit which involves more than Re .

(4) Can be extended below 1000.

TABLE 1 - CONTINUED

CODE	MASS AND THERMAL ENERGY TRANSPORT MECHANISMS			
	MOLECULAR THERMAL CONDUCTION	HEAT FLUX VARIATION		
		AXIAL FLUX VARIATION	RADIAL FLUX VARIATION	TRANSIENT CAPACITY
SUPERENERGY	YES	YES	YES	NO
ENERGY I	YES	YES	YES	NO
ENERGY II	YES	YES	YES	NO
ENERGY III	YES	YES	YES	NO

SECTION AA
VIEW LOOKING IN FLOW DIRECTION
SUBCHANNEL PATTERN AND
BUNDLE FACE NUMBERING SCHEME

FIG I-1

ORNL FFM-2A BUNDLE
(NOTE: NOT TO SCALE)

FIG 1-2

FIGURE I-3 $1\pm/1\pm$ POWER SKEW CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
 ORNL FFM-2A BUNDLE TEST 2 RUN 105
 AXIAL HEIGHT - 23" (58.42 CM) FROM BEGINNING OF HEATED SECTION

Δ - SUPERENERGY PREDICTION
 $\square$ - COBRA III C PREDICTION
 $\otimes$ - EXPERIMENTAL DATA

TEMPERATURE (°F)

TEMPERATURE (°C)

1040

1020

1000

980

960

940

920

900

560.00

548.89

537.78

526.6

515.54

504.4

493.33

482.2

1

2

3

4

5

6

BUNDLE POSITION DESIGNATION NUMBERS

FIGURE I-4 3/ POWER SKEW CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
 ORNL FFM-2A BUNDLE TEST 14 RUN 101
 AXIAL HEIGHT = 23" (58.42 CM) FROM BEGINNING OF HEATED SECTION

Δ - SUPERENERGY PREDICTION
 □ - COBRA IIIc PREDICTION
 ⊗ - EXPERIMENTAL DATA

TEMPERATURE (°F)

TEMPERATURE (°C)

BUNDLE POSITION DESIGNATION NUMBERS

760

740

720

700

680

660

640

620

1

2

3

4

5

6

404.44

393.33

382.22

371.11

360.00

348.89

337.78

326.67

-19-

CONCENTRATION (MG-SALT/LBM-WATER)

$\epsilon_H = 0.020$

- $C = 0.11$
- ◇ $C = 0.15$
- ▲ $C = 0.19$

TURBULENT

FIGURE I-5

70
60
50
40
30
20
10
0

EDGE CHANNEL NUMBER

0 2 4 6 8 10 12 14 16 18

CONCENTRATION (MG-SALT/LBM-WATER)

$\epsilon_H = 0.020$

- $C = 0.11$
- ◇ $C = 0.15$
- ▲ $C = 0.19$

TURBULENT

FIGURE I-7

$L/D = 4$
 $L = 6''$

70
60
50
40
30
20
10
0

EDGE CHANNEL NUMBER

0 2 4 6 8 10 12 14 16 18

CONCENTRATION (MG-SALT / LCM-WATER)

$C = 0.19$

-- Δ -- $\epsilon_H = 0.005$
-- $\circ$ -- $\epsilon_H = 0.01$
-- $\bullet$ -- $\epsilon_H = 0.02$
-- $\square$ -- $\epsilon_H = 0.03$

TURBULENT

FIGURE I-8

$L/D = 4$

$L = 6"$

0

2

4

6

8

10

12

14

16

18

EDGE CHANNEL NUMBER

Figure I-9

Actual Bundle
Specifications

Figure I-10

Design Bundle
Specifications

CONSTRUCTION SCHEME:

- 1) All the start points of wire wraps on the lines perpendicular to face A and through the center of the rods.
- 2) Alternate wrapping directions for each row parallel to face A.

CHARACTERISTICS: Clockwise swirl flows only happen at phases A and D.

Figure I-11
Assembly with Alternate Wire Wraps

Injection Rod in the Bundle

Figure I-12

- INJECTION RODS
- INJECTION DIRECTION
- SWEEP FLOW DIRECTION

Injection Directions and Locations of Injection Rods

Figure I-13

Reference - I

1. M.H. Fontana, R. E. MacPherson, P.A. Gnadt, L.F. Parsly, and J.W. Wantland, Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assembly in a Hexagonal Duct (Fuel Failure Mockup Bundle 2A) - Record of Experimental Data ORNL-TM-4113 (September 1973).

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

No new data was published in the literature which could be assessed this quarter.

TASK IIB: Experimental Investigation (Joseph M. Kelly)

The Barocel Pressure transducer has been received and installed along with a semi-automatic, solenoid valve actuated, sampling system. The output of the transducer (a 0-1 volt DC signal) is fed into an integrating circuit to average out the turbulent fluctuations. In measurements of the axial pressure drop, these fluctuations are about $\pm 5\%$ of the pressure, while in radial measurements they can be as much as $\pm 50\%$. The sensor has seven scales which range from full-scale outputs for 20 Psi down to .002 Psi.

Testing has begun and the pressure drop (axial and radial at every sampling plane) characteristics of the test section bundle have been obtained. Results for the axial pressure drop is presented in Fig II-1 as a graph of friction factor (f) versus Reynold's number. Mixing tests using the sampling plane at $L/D_H = 100$ are underway and should be finished during the first week of April. Then, data at the $L/D_H = 50$ plane will be taken and the results subtracted to yield the bulk mixing coefficients. After this, point concentration measurements will be taken to establish the radial concentration gradient at both measurement planes. This investigation should be finished in May, and a new researcher will take over to investigate other geometries.

TASK IIC Experimental Subchannel Local Parameter Measurements
(Laser Doppler Anemometry) - John Bartzis

The new loop using a 5HP Pump has been nearly completed. The fabrication of the test section and the entrance region is not yet complete. Since the laser equipment is being used in TASK III, measurements in this work will be started immediately after completion of TASK III-2.

TASK IID Analytic Model Development - John Bartzis

In the present report the following topics are described:

- 1) The Equations
- 2) Reynolds Stress Closure: Previous Approach
- 3) Reynolds Stress Closure: Present Approach

1. The Equations

1.1 The Reynolds Equations

Our ultimate purpose is to be able to solve the Reynolds equations within the characteristic triangle shown in Fig II-2. The Reynolds equations are the time-smoothed momentum equations obtained from the Navier-Stokes equations. In cylindrical coordinates the equations are as follows:

I. Continuity Equation

$$\nabla \cdot \underline{V} = 0 \quad (2.1)$$

II. Momentum Equations

$$r - \text{direction: } \nabla v_r \underline{V} + \nabla \tau_r = - \frac{\partial(p/\rho)}{\partial r} + \frac{v_{\theta\theta}^2}{r} + \tau_{\theta\theta} \quad (2.2)$$

$$\theta - \text{direction: } \nabla r v_{\theta} \underline{V} + \nabla \tau_{\theta} = - \frac{\partial(p/\rho)}{\partial \theta} \quad (2.3)$$

$$z - \text{direction: } \nabla v_z \underline{V} + \nabla \tau_z = - \frac{\partial(p/\rho)}{\partial z} \quad (2.4)$$

where $\underline{V}$ is the velocity vector i.e.

$$\underline{V} = (v_r, v_{\theta}, v_z) \quad (2.5)$$

∇ is the divergence operator i.e.

$$\nabla \cdot = \left(\frac{1}{r} \frac{\partial}{\partial r} r, \frac{1}{r} \frac{\partial}{\partial \theta}, \frac{\partial}{\partial z} \right) \quad (2.6)$$

p is the pressure

ρ is the density

$\underline{\tau}_r, \underline{\tau}_\theta, \underline{\tau}_z$ are stress vectors i.e.

$$\underline{\tau}_r = (\tau_{rr}, \tau_{r\theta}, \tau_{rz})$$

$$\underline{\tau}_\theta = (\tau_{r\theta}, \tau_{\theta\theta}, \tau_{\theta z})$$

$$\underline{\tau}_z = (\tau_{rz}, \tau_{\theta z}, \tau_{zz})$$

(2.7)

consisting of a laminar part, the laminar stresses and a turbulent part, the Reynolds stresses.

$$\tau_{\alpha\beta} = \tau_{\alpha\beta}^{(l)} + \tau_{\alpha\beta}^{(t)} \quad (\alpha, \beta = r, \theta, z)$$

where

$$\tau_{rr}^{(l)} = -2\nu \frac{\partial v_r}{\partial r}, \quad \tau_{rr}^{(t)} = \overline{v_r'^2}$$

$$\tau_{\theta\theta}^{(l)} = -2\nu \left(\frac{\partial v_\theta}{r \partial \theta} + \frac{v_r}{r} \right), \quad \tau_{\theta\theta}^{(t)} = \overline{v_\theta'^2}$$

$$\tau_{zz}^{(l)} = -2\nu \frac{\partial v_z}{\partial z}, \quad \tau_{zz}^{(t)} = \overline{v_z'^2}$$

(2.8)

$$\tau_{r\theta}^{(l)} = -\nu \left(r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) + \frac{1}{r} \frac{\partial v_r}{\partial \theta} \right), \quad \tau_{r\theta}^{(t)} = \overline{v_r' v_\theta'}$$

$$\tau_{\theta z}^{(l)} = -\nu \left(\frac{\partial v_\theta}{\partial z} + \frac{\partial v_z}{r \partial \theta} \right), \quad \tau_{\theta z}^{(t)} = \overline{v_\theta' v_z'}$$

$$\tau_{rz}^{(l)} = -\nu \left(\frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z} \right), \quad \tau_{rz}^{(t)} = \overline{v_r' v_z'}$$

Obviously, in order to be able to solve Equations (2.1) - (2.4) some knowledge of the Reynolds stress is required. Accurate knowledge of Reynolds stresses does not exist due to the complexity of the turbulence especially in the shear flows. Thus, approximate relations, rather crude from the scientific point of view, are used which however are very useful in solving engineering problems. The additional relations used in order to be able to solve Equations (2.1 - 2.4) consist of the Reynolds stress closure.

2. REYNOLDS STRESS CLOSURE - PREVIOUS WORK

2.1 General

As it was pointed out in the previous section, the difficulty of solving the continuity and momentum equations is strongly related to the difficulty of obtaining a Reynolds stress closure. In this section an attempt has been made of reviewing the main methods used by other investigators to obtain a Reynolds closure. The methods that will be of interest of the present work will be described in more detail.

We can distinguish three main approaches toward Reynolds stress closure.

1. Analytical expressions (i.e. semi-empirical expressions not included in the concept of eddy viscosity),
2. The eddy viscosity approach
3. Transport equations for the Reynolds stresses.

2.1.1 Analytical Expressions (Algebraic relations)

The simplest way that one could think of studying the behavior of Reynolds stresses is to try to express them as a function of the local and global characteristics of the flow which fits the experimental data. However such an approach has disadvantages, such as:

- a. Different expressions are generally needed for different geometries,
- b. The higher the number of independent parameters, the more difficult it is to obtain such analytical expressions.

Therefore such an approach seems more attractive for simple geometries (e.g. pipe flow, flow between parallel plates, boundary layer in a flat plate) or the wall regions of more complex geometries where parameters such as friction velocity u^* and local Reynolds number $y^+ = \frac{yu^*}{\nu}$ are enough to describe the Reynolds stresses. However, in the case of the simple geometries it is more logical to find analytical expressions directly for the velocity field rather than go first into the Reynolds stresses.

Parenthetically it is noticed here that in the case of pipe flow and flow between parallel plates the shear stress is given by the relation (Ref. 1, p. 50):

$$\overline{v_r'v_z'} = -\nu \frac{dv_z}{dr} + \frac{r}{r_0} u_*^2 \quad (2.1)$$

where

ν is the kinematic viscosity

r is the distance from the center line

r_0 is the diameter of the pipe or the distance between the parallel plates.

According to (2.1) an analytical expression for $\frac{dv_z}{dr}$ gives an analytical expression for $\overline{v_r'v_z'}$.

With respect to the normal stresses the only analytical expressions as far as the author knows are those obtained by V. P. Bobkov, M. Ch. Ibragimov and G. I. Savelev [2] valid for closed ducts of different form. We will mention below their expressions for the normal stress of a circular pipe since we will assume that these are also approximately valid for rod bundles.

$$\left. \begin{aligned} \overline{v_r'^2} &= A_r v_z \left(1 - \frac{u_b}{u_0}\right) e^{-A_r \xi} \\ \overline{v_\theta'^2} &= A_\theta v_z \left(1 - \frac{u_b}{u_0}\right) e^{-A_\theta \xi} \\ \overline{v_z'^2} &= A_z v_z \left(1 - \frac{u_b}{u_0}\right) e^{-A_z \xi} \end{aligned} \right\} \quad (2.2)$$

where A's and B's are constants with values:

$$\left. \begin{aligned} A_r &= 0.4 & B_r &= 1.48 \\ A_\theta &= 0.6 & B_\theta &= 1.17 \\ A_z &= 0.95 & B_z &= 1.48 \end{aligned} \right\} \quad (2.2a)$$

$$\xi = 1 - \frac{r}{r_0} \quad (2.3)$$

u_b is the bulk velocity

u_o is the maximum velocity in the channel

Equations (2.2) are valid for the center region of the flow up to $y^+ \approx 11$. The constants (2.2) fit well the experimental data in the range of $Re = 7.5 \times 10^4$ up to 2.4×10^5 .

With respect now to using algebraic expressions into the wall region, limited work has been done towards this direction. One of the reasons for this is the difficulty of obtaining reliable experimental data due to the presence of the wall. For $\overline{v'_r v'_z}$ we can use again Eq. (2.1). We will mention here the expression given by A. P. Ivanov [3] who claims that it is consistent with the experimental data of Laufer [6,7] and it is valid in the outer wall region as well. Ivanov's relation is as follows:

$$\frac{\overline{u'_r v'_z}}{u_*^2} = \frac{r}{r_o} \exp \left(- \frac{n_*^2}{1-n_*} \frac{r}{r_o - r} \right) \quad (2.4)$$

where

$$n_* = 6.6 Re^{-0.44} \quad (2.4a)$$

With respect to the normal stress - very close to the wall - analytical expressions as far as the author knows exist only for the $\overline{v_z'^2}$ very close to the wall ($y^+ < 5$).

H. Eckelman [4] gives

$$\left(\frac{\overline{v'^2}}{u_*^2} \right)^{1/2} = 0.24y^+ e^{1/2\alpha y^+} \quad (y^+ < 5) \quad (2.5)$$

where

$$\alpha \approx 0.3 \quad (2.5a)$$

2.1.2 Eddy Viscosity Approach

Instead of inventing for each case analytical expressions, it seems much more logical and practical to try to understand the general behavior of the Reynolds stresses. In other words to try to build a model for the Reynolds stresses.

Boussinesq [5] was the first to attack the problem by introducing the concept of eddy viscosity assuming that the behavior of the Reynolds shear stresses are similar to the viscous stresses. The eddy viscosity concept is the most widely used in engineering problems. The eddy viscosity concept in its most general form [8] can be expressed as:

$$\tau_{\alpha\beta}^{(t)} = \frac{\nu_{\alpha\beta}^T}{\nu} \tau_{\alpha\beta}^{(l)} + \frac{2}{3} k \delta_{\alpha\beta} \quad (2.6)$$

where

$\tau_{\alpha\beta}^{(t)}$: the turbulent Reynold stress

$\tau_{\alpha\beta}^{(l)}$: the viscous stress

k : the turbulent kinetic energy

ν : the kinematic viscosity

$\nu_{\alpha\beta}^T$: the eddy viscosity

$$\text{and } \delta_{\alpha\beta} = \begin{cases} 0 & \text{for } \alpha \neq \beta \\ 1 & \text{for } \alpha = \beta \end{cases} \quad (2.7)$$

The first term of the right hand side of Eq. (2.6) expresses the analogy between the Reynolds and the viscous stresses whereas the second term was added to satisfy two additional requirements.

- a. The sum of the normal stresses is equal to turbulent kinetic energy.
- b. In the case of absence of viscous stresses i.e. in isotropic turbulence, the normal Reynolds stresses are equal.

Such an approach could be completely successful if we could assume that the introduced eddy viscosity $\nu_{\alpha\beta}^T$ was constant like the viscosity ν . Indeed in some cases, like turbulent jets and wakes propagated in an infinite space or turbulence in a free atmosphere, such an assumption is not bad [Ref. 9, p. 365]. However in the case of closed ducts amid boundary layer, such an assumption completely fails.

So in general $\nu_{\alpha\beta}^T$ is position dependent and even worse, is

a tensorial quantity rather than a scalar. It is thus evident that in order for this approach to become practical, some knowledge of $v_{\alpha\beta}^T$ is required. Since we are going to use the same approach in the present work, this topic will be examined in more detail in §2.2.

2.1.3 Transport Equations

The idea here is that the Reynolds stresses, as the other hydrodynamic quantities, obey a transport equation which can be obtained from the Navier-Stokes equations [10] of the form

$$\text{CONVECTION} + \text{DIFFUSION} + \text{SOURCE} + \text{SINK} = 0$$

However such equations cannot be solved since they are functions of triple velocity correlations and double pressure velocity correlations. So modeling of the various terms in such equations seems necessary. Such an effort has been made by several authors such as Rotta [11], Davydov [12], Donalson [13], Daly and Harlow [14], Hanjalic and Launder [15], Naot et al. [16], Launder et al. [17].

In the present work we will not follow this approach since such an approach requires more computational time on one hand and on the other hand our geometry is not so complicated that an eddy diffusivity approach will give unacceptable results.

2.2 Eddy Diffusivity Approach

As we have pointed out before the eddy viscosity is generally not constant especially in the case of a duct flow which the rod bundle flow resembles. Therefore detailed knowledge of eddy viscosity within the flow region is necessary. There are several approaches towards this direction. The main approaches can be classified as follows:

1. Analytical expressions (Algebraic Expressions)
- 2) Prandtl Mixing Length Hypothesis
- 3) Van Karman Similarity Hypothesis
- 4) Kolmogorov-Prandtl Hypothesis
- 5) Transport Equations

2.2.1 Analytical Expressions

Efforts to express the eddy viscosity as an analytical function of the local and global characteristics of the flow in simple flows have appeared in literature. Reichardt [18] has developed an eddy viscosity expression for the parallel plate geometry.

$$\nu_{rz}^T = \frac{k}{3} \left(1 - \frac{r}{r_o}\right) \left[0.5 + \left(\frac{r}{r_o}\right)^2\right] \left[1 + \frac{r}{r_o}\right] u^* \quad (2.8)$$

where

$$k \approx 0.4 \quad (2.8a)$$

Eifler [19,20] has generalized v_{rz}^T for round tubes, parallel plates and concentric annuli which have been applied satisfactorily for the rod bundles geometry [21]:

$$v_{vz}^T = y_o \frac{K'}{2(1+b)} [b+x^2][1-x^2] \frac{2K - x(k-1)}{(K+1)[K-2(K-1)]} u^* \quad (2.9)$$

$$x = 1 = \frac{y}{y_o} \quad (2.9a)$$

$$K = \begin{cases} 1 & \text{for parallel plates} \\ 0 & \text{for circular tubes} \\ 1 + \frac{y_o}{R} & \text{for flows outside a rod of radius } R \end{cases} \quad (2.9b)$$

$$K' = \begin{cases} 0.407 & \text{for parallel plates or pipe flow} \\ 0.407 + 0.02 y_o/R & \text{for flows outside a circular rod} \end{cases} \quad (2.9c)$$

$$b = \begin{cases} 0.55 & \text{for parallel plates and pipe flows} \\ [1.8] - 1.3 (y_o/R)[1. + 0.14 (\log Re_\ell - 5)]^{-1} & \text{for flows outside a circular rod} \end{cases} \quad (2.9d)$$

y_o is the radial distance between the wall and the zero shear stress line

and

Re_ℓ is the local Reynolds number at the peripheral position considered.

With respect to the lateral eddy viscosity, Nijssing and Eifler [21,22] use an average of $v_{\theta z}^T$ over the radial direction of the form

$$v_{\theta z}^T \approx c y_0 u^{\#} \quad (2.30)$$

with $c \approx 0.185 \quad (2.30a)$

Eq. (2.30) reflects the experimental evidence [23] that the lateral eddy viscosity is higher than radial eddy viscosity.

Rapier and Redman [24] take

$$c \approx 0.1 \quad (2.30b)$$

2.2.2 Prandtl Mixing Length Hypothesis

Efforts to understand the general behavior of eddy viscosity has been carried out by several authors. The main idea behind these efforts is that the eddy viscosity taking into consideration the analogy that the viscosity can be expressed as a product of a velocity scale U times a length scale ℓ , i.e.

$$v^T \sim U \cdot \ell \quad (2.31)$$

The velocity scale U can be associated with representative velocity of the fluid eddies in a particular position. The length scale ℓ can be considered as the representative length an eddy travels before losing its identity. This is the

basis of Prandtl's mixing length theory [25]. In developing his hypothesis we will refer to the simplest case of parallel flow. According to Prandtl

$$v'_z \sim v'_r \sim \ell' \frac{d\bar{v}_z}{dz} \quad (2.32a)$$

where v'_r , v'_z represent the fluctuation velocities of fluid lumps arriving at r from the position $r + \ell'$ and $r - \ell'$. In such cases, the velocity scale U can be expressed as:

$$U \sim \ell \left| \frac{dv_z}{dz} \right| \quad (2.32b)$$

where ℓ is of the order of the root mean square of the random length ℓ' . Thus Eq. (2.31) becomes

$$v_{rz}^T \approx \text{const } x \ell^2 \left| \frac{dv_z}{dz} \right| \quad (2.33)$$

l is the Prandtl's mixing length. l is not a constant but depends generally on the position under consideration and is usually given by analytical expressions based on experimental data. A more general form for the mixing length has been given by Buleev [26]

$$\frac{1}{l} = \text{const} \times \int_{\Omega} \frac{d\Omega}{l(\Omega)} \quad (2.34)$$

where Ω denotes the direction

and $l(\Omega)$ is the distance of the point under consideration from the wall in the direction Ω .

Prandtl's similarity hypothesis has been successfully applied to the study of turbulent motion along walls (pipe, channel, plate) and in free turbulent flows (see for example, Ref. 27, Chapters XIX, XX, XXI, XXIV).

In rod bundles it has been applied by Bender et al. [27,28]. For l Buleev's formula (2.34) is used.

However Prandtl's similarity hypothesis proved to be unsatisfactory in the region where $\frac{dv_z}{dy} = 0$ since it gives zero eddy diffusivity which is in contrast with the experimental evidence which gives considerably higher values of eddy viscosity.

2.2.3 Von Karman Similarity Hypothesis

Prandtl's theory does not solve completely the problems of eddy viscosity behavior since it does not say anything about the behavior of ℓ . A general hypothesis which allows us to establish a general connection between the length ℓ and the mean velocity field was proposed by Von Karman [26]. His approach is called "the local kinematic similarity hypothesis". According to this approach the turbulent fluctuations are similar at all points of the field. They differ from point to point only by time and length scales or equivalent length and velocity scales. Quantitatively such an assumption leads to the following relation for the velocity scale and length scale:

$$u \sim \frac{dv_z}{dz} \quad (2.35)$$

$$\ell \sim \frac{dv_z / dz}{d^2 v_z / dz^2}$$

Consequently the Karman similarity hypothesis gives the following relations for the shear stress which is essentially the same with Eq. (2.33)

$$\tau_{rz}^T = \ell^2 \left| \frac{dv_z}{dz} \right| \left| \frac{dv_z}{dz} \right| \quad (2.36)$$

where

$$l = k \frac{dv_z / dy}{d^2v_z / dy^2} \quad (2.36a)$$

and k is called the Von Karman constant as it is equal to 0.4.

Von Karman's hypothesis imposes excessively rigid constraints in the velocity fluctuations which do not generally agree with experimental evidence [30, p. 107].

2.2.4 Kolmogorov - Prandtl Hypothesis

Prandtl's mixing length hypothesis and Von Karman's similarity hypothesis reflects the effort to find a relation between eddy viscosity and the characteristics of the mean flow. Other efforts on the same line of approach have been made such as Taylor's vorticity transfer theory [31], improved theories of Prandtl's mixing length hypothesis [44, p. 549], Buleev's theoretical model for turbulent transfer [26] and its modification by Ramm [32] for the case of rod bundle geometry.

The above models do not directly take into consideration statistical characteristics of turbulence upon which the eddy viscosity depends.

The first attempt to express eddy viscosity as a function of the turbulent characteristics of the turbulence is due to Kolmogorov [33] who postulated a characteristic turbulent frequency f .

If we assume that the length scale ℓ and velocity scale U (of Eq. 2.31) are functions of the turbulent kinetic energy k and the frequency f we can find immediately from dimensional analysis that

$$U \sim k^{1/2} \quad (2.37a)$$

$$\ell \sim \frac{k^{1/2}}{f} \quad (2.37b)$$

and consequently

$$\nu^T = \text{const} \times \frac{k}{f} \quad (2.38)$$

Prandtl [34] has substituted where for the velocity the relation [2.37a]. In such a case, equation [2.38] becomes

$$\nu^T = \text{const} \times k^{1/2} \times \ell$$

where ℓ is the length scale equivalent with the mixing length used in [2.33].

It is evident from the above discussion that any quantity z which is assumed to be a function of k and l only (like f in 2.38) can be expressed by dimensional analysis in the form of :

$$z = k^{\alpha} l^{\beta} \quad (2.40)$$

Then, one can write v^T from Eqn 2.31 as a function of k and z as follows:

$$v^T = \text{const} \times k^{1/2 - \alpha/\beta} z^{1/\beta} \quad (2.41)$$

Eqn. [2.41] is a general relation of eddy viscosity as a function of the statistical characteristics k and z . However, the utilization of [2.41] requires the knowledge of k and z . This can be obtained either by semi-empirical equations or by transport equations for k and z . The way of evaluating k and z defines the type of the turbulence model as 0-equation model, 1- equation model and 2-equation model where the term "equation" refers to transport equations for k, z .

0-Equation Model

In this case k and l are prescribed by semi-empirical equations. This model will be applied in this work for comparison with 1- and 2- equation models.

1-Equation Model

In this case a transport equation for k is used whereas ϵ is described by a semi-empirical relation. This model has been widely used (see references in 35 and 36). With respect to the closed channel flows and rod bundles the 1-equation model is applied by Launder and Ying [37] and P. Carajilescov [38] in square ducts and rod bundles respectively.

The transport equation for k can be obtained from the Navier-Stokes equation. The way of modeling it is similar to that discussed in §2.1.3 concerning the Reynolds stresses themselves although the task is much easier as we will see later.

2-Equation Model

In this model transport equations are required for both k and ϵ . In the literature one can find a variety of ϵ 's picked up by different authors as we can see from Table II-1 taken from [39].

The transport equation for ϵ usually is found by one of two ways:

- 1) Derivation from Navier-Stokes equation. For example, a transport equation for the turbulent energydissipation ϵ can be obtained [40, 41]. Such a procedure however, is not easy for all ϵ . Therefore, the second procedure is sometimes used.

2) Derivation from turbulent kinetic energy and dimensional analysis. To be more specific the turbulent kinetic energy according to what we have said in § 2.1.3 can be written:

$$\text{convection (k)} + \text{diffusion (k)} + \text{source (k)} + \text{sink (k)} = 0 \quad (2.42)$$

The transport equation for z will have the form

$$\begin{aligned} \text{Convection (z)} + \text{diffusion (z)} + \text{const} \times \frac{z}{k} \text{ source (k)} + \\ + (\text{const})' \times \frac{z}{k} \text{ sink (k)} \end{aligned} \quad (2.43)$$

where the constants have to be determined from the experiment.

From the relations (2.41) or (2.43) it is evident that such an approach presupposes the adequacy of k and z for describing the "integral" behavior of turbulence at particular points. However, this cannot be true for nonisotropic turbulence where more than one velocity scale and/or length scale exists. Monin [9] has proposed the following alternative relation in such a case for the Reynolds stresses based on the fact that the Reynolds stress is a second order symmetric tensor and the assumption that the Reynolds stress can be expressed as a linear combination of the mean strains:

$$\overline{u'_\alpha u'_\beta} = \frac{2}{3} k \delta_{\alpha\beta} - \frac{1}{2} k^{1/2} \sum_i \left(l_{\alpha i} \frac{\tau_{i\beta}^{(l)}}{v} + l_{\beta i} \frac{\tau_{i\alpha}^{(l)}}{v} \right) \quad (2.44)$$

where $\frac{\tau_{i\beta}^{(l)}}{v}$, $\frac{\tau_{i\alpha}^{(l)}}{v}$ is the mean strain

and $l_{\alpha\beta}$ are the length scales to be determined.

However, such a relation which includes the unknowns $l_{\alpha\beta}$ is rather difficult to utilize to solve engineering problems.

The other alternative are to use Eq. (2.41) or (2.43) but the constants have to be functions of the position under consideration and/or length scales which are functions of the direction as well. However, it is logical and the experimental work has shown that in flows with not too large mean velocity gradients, the Prandtl-Kolmogorov approach gives quite reasonable results where the constants are not universal any more but depend slightly on the case under consideration. Such flow conditions can be considered to be achieved in flows within a closed duct or a rod bundle excluding the wall region (i. e. $y^+ > 30$) at a high Reynolds number.

Flows at low Reynolds numbers or inside the wall region requires a position dependent constant if one wants to use Kolmogorov-Prandtl approach successfully.

It is reasonable to expect that the introduction of more than one length scale in Kolmogorov-Prandtl's model will considerably improve the results especially when we go closer to

the wall. In the present work the Kolmogorov-Prandtl approach will be used introducing two length scales; one length scale normal to the wall and one in the lateral direction (see later report).

With respect to the selection of procedure 2) for Z , the energy dissipation ϵ is selected which is the most widely used.

From the dimensional analysis

$$\epsilon \sim k^{3/2} z^{-1}$$

so from Eq. (3.41.) for $\alpha = \frac{3}{2}$ $\beta = -1$ we obtain

$$v^T \sim k^2 / \epsilon$$

The precise expression for eddy viscosity as well as the modeling of k and ϵ equations will be given later in the description of present analytical model.

2.2.5 Transport Equation

A logical thought originating from Eq. (2.41) is to use for z the eddy viscosity itself assuming it is isotropic. This idea has been put forward by Nee and Kovasznay [42]. A transport equation for v^T is used also in code VAR-II [43] dealing with the solution of 2-dimensional transient flows.

This approach is another alternative based on Kolmogorov-Prandtl approach which makes more difficult the introduction of a non-isotropic eddy viscosity.

3.0 REYNOLDS STRESS: CLOSURE: Present Approach

3.1 General

As we have pointed out in the previous section, the eddy viscosity approach is used for obtaining a Reynolds stress closure. The reason was that the flow is not very complicated so that transport equations for Reynolds stresses are not requested. From all the eddy viscosity approaches the Kolmogorov-Prandtl hypothesis is adopted since it relates eddy viscosity directly to the turbulence characteristics of the flow which are the "natural" parameters. The most advanced model based on Kolmogorov-Prandtl hypothesis is the 2-equation model in which transport equations for turbulent kinetic energy k and other characteristic quality of the turbulence z are used. The selection of z varies from author to author. We select for z the energy dissipation ϵ which is the more widely used. Calculations with 0-equation model and 1-equation model will be performed for comparison with 2-equation model.

It is repeated here that the authors who use the Kolmogorov-Prandtl hypothesis considering the viscosity isotropic are not consistent with the experimental evidence [23]. In this approach we will try to use more than one length scale (i.e. anisotropic eddy viscosity) the estimation of which are based on simple experimental observation.

3.2 Shear stress relations

In the present approach the shear stresses will be expressed as follows:

$$\overline{v_r' v_z'} = -v_{rz}^T \frac{\partial v_z}{\partial r} \quad (3.1)$$

$$\overline{v_\theta' v_z'} = -v_{\theta z}^T \frac{\partial v_z}{r \partial \theta} \quad (3.2)$$

$$v_r' v_\theta' = -v_{r\theta}^T \left| r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) + \frac{1}{r} \frac{\partial v_{r'}}{\partial \theta} \right| \quad (3.3)$$

We will further assume

$$v_{r\theta}^T \approx v_{rz}^T \quad (3.4)$$

for the following reasons:

- 1) $\overline{v_r' v_\theta'}$ does not play an important role in the creation

of the secondary flow [52] so a very accurate knowledge of $\overline{v_r' v_\theta'}$ is not necessary. In fact, M. Kh. Ibragimov et al. [53] and P. Carajilescov [1] neglect $\overline{v_r' v_\theta'}$ in their calculations so a more accurate knowledge of $v_{r\theta}^T$ seems worthless.

- 2) $\overline{v_r' v_\theta'}$ includes v_r' fluctuations and v_θ' is expected to have a length scale closed to v_z' .

3.2 Eddy viscosity for Shear Stresses

In this approach the eddy viscosities v_{rz}^T and $v_{r\theta}^T$ will be expressed as follows:

0 or 1 - Equation Model

$$v_{rz}^T = c_v k^{1/2} l_r \quad (3.5)$$

$$v_{\theta z}^T = c_v k^{1/2} l_\theta \quad (3.6)$$

where c_v will be a constant such that the l_{rz} will be equal to distance from the wall in the vicinity of $y^+ = 30$.

2 - Equation Model

Based on the relations (3.5), (3.6) and (2.45) the eddy viscosity relations are as follows:

$$v_{rz}^T = c_\mu k^2 / \epsilon \quad (3.7)$$

$$v_{\theta z}^T = c_\mu \frac{l_\theta}{l_r} k^2 / \epsilon \quad (3.8)$$

It is evident from the above formulations that the eddy viscosity ratio is given by the relation

$$\psi_m = \frac{v_{rz}^T}{v_{r\theta}^T} = \frac{l_r}{l_\theta} \quad (3.9)$$

Thus additional knowledge for ψ_m is needed.

3.3 The Length Scales

Viscosity ratios are given in the literature especially for the fully developed flow condition in rod bundles from authors that do not use Kolmogorov-Prandtl's approach e.g. Nijssing and Eifler [22]. However, such a ratio is strongly related to the models for $v_{\theta z}^T$ and v_{rz}^T adopted which are different from our approach. Here we will try to estimate l_r and l_θ from empirical relations based on experimental observations.

3.3.1 The Length l_r

We will restrict our discussion to the region $y^+ \geq 25-30$ since it represents the region where the calculations are to be performed. It is called the outer region of the flow. The region $y^+ < 25$ which is very close to the wall is characterized by sharp velocity gradients and strongly anisotropic turbulent kinetic energy distribution. So a model based on a Kolmogorov-Prandtl hypothesis seems not beneficial although effort towards this direction have been made by some authors [50, 52]. Even worse, the calculation of hydrodynamic characteristics within the wall region directly from the equation needs relatively high computational effort due to the large number of points needed for the numerical calculations.

However, things can be simplified considerably in the case of not very high acceleration or deceleration due to the fact that the hydrodynamic characteristics are satisfactorily described by u^* and y^+ only. Returning to

the outer region (i.e. $y^+ \geq 25 - 30$) let us see the length scales taken by some authors.

Launder and Ying [37] in the case of rectangular duct flow use Buleev's formulation [Eq. 2.3.4] i.e.

$$\frac{1}{\lambda} = \int_0^{2\pi} \frac{d\phi}{s} \quad (3.10)$$

Such a relation gives λ proportional to the wall distance for points very close to the wall.

D. Naot et. al [54] in the case of rectangular duct flow tube used.

$$\begin{aligned} \lambda &= y \quad 0 \leq y \leq 0.54 D_H \\ \lambda &= 0.135 D_H \quad 0.135 D_H < y \leq \frac{D_H}{2} \end{aligned} \quad (3.11)$$

where y is the distance from the wall and D_H is the hydraulic diameter of the flow.

P. Carajilescov [1] in the case of rod bundles, takes the relation

$$\begin{aligned} \lambda &= y \text{ for } 0 \leq y \leq 0.44 \hat{y} \\ \lambda &= 0.44 \hat{y} + 0.066 \hat{y} \sin \left| \frac{\pi}{0.38} \left(\frac{y}{\hat{y}} - 0.44 \right) \right| \end{aligned} \quad (3.12)$$

Where $\hat{y}$ is the radial distance of the centerline from the wall at a particular angle θ .

Relations (3.10)(3.11) and (3.12) agree to the point that

$$z \sim y \text{ close to the wall} \quad (3.13)$$

In this approach we will distinguish three subregions within the outer region:

- A. The dynamic equilibrium subregion
- B. The central subregion
- C. The subregion in between

3.3.1.1 The Dynamic Equilibrium Subregion

The dynamic equilibrium subregion is the region closer to the wall and has the following characteristics:

- a) The diffusion and convective mechanisms of turbulent kinetic energy transport are small compared with source and dissipation mechanisms. In this region turbulent kinetic energy has its highest values whereas the turbulent kinetic energy gradients are relatively small. In other words, if δk is the change of kinetic energy within this region and k_0 is a representative value of the turbulent kinetic energy level the following relation holds:

$$\frac{\delta k}{k_0} \ll 1 \quad (3.14)$$

Thus in such a case we can approximate

$$k \approx k_0 \neq f(r)$$

b) The shear stress $\overline{v'_r v'_z}$ is approximately constant.

A good approximation consistent with the experimental evidence is that

$$\overline{v'_r v'_z} \approx u_*^2 \neq f(r) \quad (3.15)$$

If we want to put $\overline{v'_r v'_z}$ in the form of (3.1) using the relation (3.5), Eq. (3.15) leads to the following relation for ℓ_{rz} :

$$\ell_r \approx \frac{1}{c_v} \frac{u_*}{k_0^{1/2}} \frac{u_*}{dv_z/dr} \quad (3.16)$$

Since k_0 is mainly a function of u^*

$$\frac{1}{c_v} \frac{u_*}{k_0^{1/2}} \approx \text{const} \quad (3.17)$$

In the principle we can pick up any value we want for the const. The most reasonable choice is to take it as unity. However, in order to have the same order of magnitude for the constants with other investigators who take $\ell_r = y$ we will define the above constant as follows.

Within dynamic equilibrium region the logarithmic law is expected to be valid i.e.

$$\frac{dv_z}{dr} = \frac{u_*}{ky} \quad (3.18)$$

when k is the Von Karman constant i.e.

$$k \approx 0.4$$

So we take

$$\frac{1}{c_v} \frac{u^*}{k_o^{1/2}} = \frac{1}{k} \quad \text{or} \quad c_v = \frac{u^* k_o}{k_o^{1/2}} \quad (3.20)$$

c_v has to be determined from the experiment

$$l_r = \frac{1}{k} \frac{u^*}{dv_z/dr} \quad (3.21)$$

within the dynamic equilibrium subregion.

3.3.1.1 The Central Region

The central region is characterized by small or zero velocity energy gradients. The selection of l constant and proportional to the distance between the wall and the zero shear stress line gives satisfactory results i.e.

$$l_r = c_L y \quad (3.22)$$

The value of c_L has to be found from the experimental data. A quick estimation can be found however from the simple geometries as pipe flow for $c_v \approx 0.2$

$$\left. \frac{k^{1/2}}{u^*} \right|_{y=y} \approx 0.9 \quad (3.23)$$

$$\left. v_{rz}^T \right|_{y=y} \approx 0.07 u^* y \quad (3.24)$$

we find $c_L \approx 0.4$ (3.22)

which is in a good agreement with P. Carajilescov [1] who takes at zero shear stress line $c_L = 0.374$ and higher values for points outside the zero shear stress line.

3.3.1.3 The Intermediate Subregion

The bigger subregion in the outer flow region is the intermediate region which has neither the properties of the dynamic equilibrium region nor the properties of the central region. In this region it is reasonable to assume that the

$$l_r = f_l \left(\frac{dv}{v^* dr}, \hat{y} \right) \quad (3.23)$$

a logical approximation for the function can be the following

$$\left(\frac{1}{l_r} \right)^\alpha = \left(k \frac{dv_f/dr}{u^*} \right)^\alpha + \left(\frac{1}{c_L \hat{y}} \right)^\alpha \quad (3.24)$$

Where α a real number to be determined from the experiments. Preliminary calculations by the author shows that α is of order 2, probably higher.

If dv_z / dr is small as it happens in the central subregion, Eq. (3.24) is reduced to Eq. (3.22).

When the dv_z/dr is large as it happens in the dynamic equilibrium subregion, eq. (3.24) is reduced to (3.21)

Thus Eq. (3.24) prescribes ℓ_r for the whole outer region of the flow.

The physics behind this model is that the length scale is not a pure geometric characteristic of the flow. In some sense it reflects the distortion of the turbulent kinetic energy wave length spectrum due to the presence of the non-uniform velocity field which is quite reasonable.

It is worth to point out here that this relation does not predict a maximum value outside the zero shear stress line as the relation of P. Carajilescov [1] predicts. Let us however keep in mind that P. Carajilescov based his relation on his experimental data which includes a relatively large error in quantities such as $\overline{v_r'v_z'} k^{1/2}$ and dv_z/dr .

The Length Scale ℓ_θ

In order to estimate ℓ_θ the following assumptions will be made.

1) $v_{rz}^T \approx v_{\theta z}^T$ in the central region. This is a quite reasonable assumption taking into consideration the fact that $\overline{v_r'^2}$, $\overline{v_\theta'^2}$, $\overline{v_f'^2}$ are of the same order of magnitude (i.e.

$$\overline{v_z'^2} : \overline{v_r'^2} \approx \overline{v_\theta'^2} = 1.16 : 1 : 1, [2]).$$

2) Neglect the effect of $\frac{dv_z}{dr}$ on ℓ_θ as a second order effect.

3) A similar expression to (3.24) holds for ℓ_θ i.e.

$$(1/\ell_\theta)^\alpha = (c_3 \frac{dv_z / rd\theta}{u^*})^\alpha + (\frac{1}{c_4 y})^\alpha \quad (3.25)$$

where c_3, c_4 constants in our case we expect $dv_z / rd\theta$ to be small so for simplicity we approximate

$$\ell_\theta \sim c_4 y \quad (3.26)$$

Since we have assumed isotropy in the central region

$$\ell_\theta \sim c_L y \quad (3.27)$$

where C_L is given by (3.23)

The length scale ratio (or the eddy viscosity ratio) is given by the relation

$$\psi_m = \frac{v_{rz}^T}{v_{r\theta}^T} = \frac{\ell_r}{\ell_\theta} = \left| 1 + [c_L \frac{dv_z/dr}{u^*/ky}]^\alpha \right|^{-\alpha} \quad (3.28)$$

It is worth to point out here that ℓ_r given by (3.27), gives results in agreement with the experimental evidence (See APPENDIX I).

4. Numerical Work

The computer program which is under development has two main options:

- 1) no secondary flow,
- 2) secondary flow included

The no secondary flow option has not created any problem and seems to work satisfactorily.

The secondary flow option appears to have severe problems with respect to the convergence of the secondary flow component.

Details of the numerical work will be published in a later report.

NOMENCLATURE

Symbol

Definition

k

Turbulent kinetic energy =

$$k = \frac{\overline{v_r'^2} + \overline{v_\theta'^2} + \overline{v_z'^2}}{2}$$

r

Distance from the centerline of a pipe or parallel plates

u_o

Maximum channel velocity

u_b

Bulk velocity

u^*

viscous velocity = $u^* = \sqrt{\frac{\tau_w}{\rho}}$

$\underline{v} = (v_r, v_\theta, v_z)$ Time mean velocity vector

y

Distance from the Wall

ϵ

Energy dissipation =

$$\epsilon = \nu \sum_{\alpha, \beta} \left(\frac{\partial v_\alpha'}{\partial x_\beta} \right)^2$$

$l_{\alpha\beta}$

length scale

$\tau_{\alpha\beta}^{(l)}, \tau_{\alpha\beta}^{(t)}$

Laminar and Reynolds stresses

AUTHOR	Z NAME	Z DEFINITION	TURBULENT VISCOSITY	
Kolmogorov [33]	frequency	$f = c \frac{k^{1/2}}{l}$	$\nu_t = \frac{k}{f} = k^{1/2} l$	
Rotta [45]	length-energy product	$L = kl$		Duct Flow
Rodi & Spalding [46]	length-energy product	$L = kl$	$\nu_t = k^{1/2} l$	Free shear flows
Ng & Spalding [67]	length-energy product	$L = kl$	$\nu_t = k^{1/2} l$	Boundary layers
Wolfshtein [48]	"	$L = kl$	$\nu_t = 0.22 k^{1/2} l$	One-dimensional flows
Glushko [44]	length squared	$\lambda = \frac{1}{2} l^2$	$\nu_t = \alpha l k^{1/2}$ $0.2 < \alpha < 0.8$	High turbulence version of a low turbulence model applied to trans. flat plate boundary layer
Harlow & Nakayama [41]	Dissipation	ϵ	$\nu_t = 0.2 \frac{k^2}{\epsilon} = 1.41 k^{1/2} l$	
Jones & Launder [50]	"	ϵ	$\nu_t = 0.09 \frac{k^2}{\epsilon}$	High turbulence version of a low turb model applied to laminarizing Boundary layer.
Wilcox & Alber [51]	Vorticity squared	Ω^2	$\nu_t = \frac{k}{\Omega} = k^{1/2} l$	Boundary layers.

Table II-1
Parameters Z (taken from Reference 39)

Figure II-1

Fig II-2. Characteristic triangle for the study of fully developed flow in an infinite triangwave array of bare rods

REFERENCES

TASK II

1. P. Carajilescov, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle", MIT Ph.D Thesis, 1975.
2. V. P. Bobkov et al., "Correction of Experimental Data on the Pulsation Velocity Intensity for Turbulent Fluid Flow in Channels of Different Form: Izv AN SSR Mekhanika Zhidkosti i Gaza Vol. 3, No. 3, (English Translation pps 111-113) (1968).
3. A. P. Ivanov, "Turbulent Friction in the Flow of Liquid in Tubes and Channels" Izv. AN SSSR Mekhanika pps 311-316) 1972.
4. H. Eckelmann, "The Structure of the Viscous Sublayer and the Adjacent Wall Region in a Turbulent Channel Flow", J. Fluid Mechanics, Vol. 65, Part 3, pp. 439-450, 1974.
5. J. Boussinesq, "Essai sur la Theorie des Eaux Courantes", Mem pres par div. savants a l'Acad Sci Paris, 23, No. 1, 1-680, 1877.
6. J. Laufer, "The Structure of Turbulence in Fully Developed Pipe Flow," NACA Report No. 1174, 1954.
7. J. Laufer, "Investigation of Turbulent Flow in a Two Dimensional Channel", NACA Report No. 1053, 1951.
8. F. H. Harlow and P.I. Nakayama, "Turbulence Transport Equations", The Physics of Fluids, Vol. 10, No. 1, pps 2323-2332, 1967.
9. A. S. Monin and A.M. Yaglom, "Statistical Fluid Mechanics" Vol. 1, the MIT Press, 1961.
10. P.Y. Choi, "On Velocity Correlation and the Solutions of the Equations of Turbulent Fluctuation" Quart. Appl. Math 3, 31, 1945.
11. J. Rotta, "Statistische Theorie Nichtstationarer Turbulenz" Zeitschrift für Physik, Bd 129, S. 547-572, 1951.
12. B. I. Davydov, "On the Statistical Dynamics of an Incompressible Turbulent Fluid" Dokl. AN SSSR Vol. 4, (English Translation pps 769-772), 1968.

3. C. P. Donalson, "A Computer Study of an Analytical Model of Boundary Layer Transition, AIAA, 1968.
14. Daly, B.J., and Harlow, F.H., "Transport Equations in Turbulence" Physics of Fluids 13 2634, 1976.
15. Hanjalic, K. and Launder, B.E., "A Reynolds Stress Model of Turbulence and its Application to Thin Shear Flows", J. Fluid Mech 52, 609, 1972.
16. Dan Naot, "The Influence of the Pressure Fluctuation on the Redistribution of the Velocity Correlation in Turbulent Flow, DScThesis Technion-Israel Institute of Technology, Haifa, May, 1972.
17. Launder, B.E., Reece, G.J. and Rodi, W., "Progress in the Development of a Reynolds Stress Turbulence Closure" J. Fluid Mechanics, 1975.
18. Reichardt, H. "Vollständige Darstellung der Turbulenten Geschwindigkeitsverteilung in Glatten Leitungen Z. Angew. Math. Mech 31, 208-219, 1951.
19. Eifler, W. "Über die Turbulente Geschwindigkeitsverteilung und Wandreibung in Strömungskämen Verschiedene Querschnitte" Doctoral Thesis T.H., Darmstadt, 1968.
20. Eifler W. "Calculation of Turbulent Velocity Distribution and Skin Friction in Concentric Annuli" Wärme und Stoffübertragung 2, 36-46, 1969.
21. R. Nijssing and W. Eifler, "Axial Development of Temperature Fields in Hexagonal Fast Reactor Fuel Rod Assemblies with Liquid Metal Cooling: Karlsruhe Meeting Paper No. 60, 1973.
22. Nijssing R. and Eifler W., "Temperature Fields in Liquid Metal Cooled Rod Assemblies" Progress in Heat and Mass Transfer, Vol. 7, pp. 115 - 149, 1973.
23. Nijssing, R., Personal Communication
24. Rapiert, A.C. and Redman, J.D.R., "The Calculations of the Velocity Distributions in Rod Clusters" TRG - Report [W] Reactor Development Laboratory, Windscale, UK, 1964.
25. Prandtl, L., "Über die ausgebildete Turbulenz ZAMM 5, 136-139, 1925.
26. Buleev, N.I., "Theoretical Model for Turbulent Transfer in 3-Dimensional Flows: Paper No. 329 presented at the 3rd UN Int. Conf. on Peaceful Uses of Atomic Energy in Geneva, 1964.

27. Bender, D.J. and Magee, P.M. "Turbulent Heat Transfer in a Rod Bundle" ASME 68 - WA/HT-36., 1969.
28. Bender, D.J. and Magee, P.M. "Turbulent Heat Transfer in a Rod Bundle with Liquid Metal Coolant", GEAP-10052, 1969.
29. Th. Von Karman "Mechanische Ahnlichkeit und Turbulenz" Coll. Works II 337- 346, 1931.
30. Cebeci T., Smith, A.M.O., "Analysis of Turbulent Boundary Layers" Academic Press, 1971.
31. Taylor, G.I., "The Transport of Vorticity and Heat Through Fluids in Turbulent Motion" Proceedings of the Royal Society, A Vol. CXXXV pps 685-705, 1932.
32. Ramm, H. and Johannsen, K. "A Phenomenological Turbulence Model and its Application to Heat Transport in Infinite Rod Arrays with Axial Turbulent Flow: J. of Heat Transfer, pps. 231-237. 1975.
33. Kolmogorov, A.N., "Equation of Turbulent Motion of an Incompressible Fluid (in Russian) 12V Akad. SSST ser. phys Vol III, No. 1.2, 1942.
34. Prandtl, L. "Uber ein neues formelsystem fur die ausgebildete Turbulenz" Ludwig Prandtl Gesammelte Abhandlungen, Springer-Verlag P. 874-887, 1945.
35. Launder, B.E. and Spalding, D.B., "Mathematical Models of Turbulence" Academic Press, 1972.
36. Gosman, A.D.; Pun, W.M.; Runchal, A.K.; Spalding, D.B. and Wolfshtein, M. Heat and Mass Transfer in Recirculating Flows, Academic Press, London, 1969.
37. Launder and Ying, "Prediction of Flow and Heat Transfer in Ducts of Square Cross Section", The Institution of Mech. Eng. Proceedings, Vol. 187, 37/73 pp. 455-461., 1972.
38. Tennekes, H., and Lumley, J.L., "A First Course in Turbulence" the MIT Press, 1972.
39. Wolfshtein M. , Naot D. and Lin, A., "Models of Turbulence" Report NE-746 Ben Gurion University of the Negev, 1974.
40. Davydov, B.I., "On Statistical Dynamics of our Incompressible Turbulent Fluid" Soviet-Physics Doklady Vol 6, No. 1, pps 10-12, 1961.

1. Harlow, F.H. and Nakayama, A.I. "Transport of Turbulence Decay Rate" Los Alamos Report 3854, 1968.
42. Nee and Koraszny, "Simple Phenomenological Theory of Turbulent Shear Flows" The Physics of Fluids 12, 3 pps 473-484.
43. Cook, J.L.; Nakayama, P.I., "VARR-II A Computer Program for Calculating Five Dependent Turbulent Fluid Flows with Slight Density Variations" WARD-D-0106 Vol. 1, May 1975.
44. Schlichting, H., "Boundary Layer Theory" Translated by J. Kestin McGraw Hill, 1968.
45. Rotta, J.C. Über eine methode zur berechnung turbulenter Scherströmungsfelder, Aerodynamische Versuchsanstalt Göttingen 69A14.
46. Rodi, W. and Spalding, D.B. A Two-Parameter Model of Turbulence and its Application to Free Jet, Wärme und Stoffübertragung 3 85, 1970.
47. Ng, K.G. and Spalding, D.B., Turbulence Model for Boundary Layer near Walls, Physics of Fluids, 15 1, 20-30, 1972.
48. Wolfshtein M. "On the Length-Scale-of Turbulence Equation" Israel Journal of Technology 8, 1-2, 87-99, 1969.
49. Glushko, G.S. "Differential Equation for the Scale of Turbulence and Calculation of the Turbulent Boundary Layer on a Flat Plate Fluid Mechanics - Soviet Research 1, 2 155-162, (1972)
50. Jones, W.P. and Launder, B.D., The Prediction of Laminarization with a Two Equation Model of Turbulence, Int J. Heat Mass Transfer 15 301, 1972.
51. Wilcox, D.C. and Alber I.E., "A Turbulence Model of High Speed Flows" proceedings of Heat Transfer and Fluid Mechanics Institute 14-16 June 1972, Northridge, Calif, Standord, Univ. Press, 1972.
52. Brundrett, E. and Baines, W.D., "The Production and Diffusion of Vorticity in Duct Flow", J. Fluid Mechanics, Vol 19, pps 375-394, (1964).
53. M. Kh Ibragimov, V.S. Petrishchev, and G. I. Sabelev, "Calculation of Secondary Flow in a Turbulent Fluid Stream" Izv An SSSR Mekhaniko Zhidkosti i Gaza vol 4, No. 4, (1969) English translation pps 114 - 116.

54. D. Naot, A. Shavit and M. Wolfshtein, "Numerical Calculation of Reynolds Stresses in a Square Duct with Secondary Flow" *Wärme- Stoffübertragung* 7(1975) pps 151-151.
55. W. M. Rohsenow, H. Choi, "Heat Mass and Momentum Transfer" Prentice-Hall, Inc. (1961).

APPENDIX I

Length Scale ℓ_θ - Comparison with Experimental Results

I.1 General

A tabulation of experimental data made by various authors with respect to the lateral diffusivity on closed ducts by using tracer and heat dispersion techniques made by Nijssing et al. [23] show that the average eddy lateral viscosity along the radial direction is given by

$$\overline{v_{\theta z}^T} \approx (0.12 \div 0.21) u_* \eta \quad (I.1)$$

In this APPENDIX we will try to show the present model for

$\overline{v_{\theta z}^T}$ agrees sufficiently with (I.1) For this purpose we will assume simple geometry (i.e. parallel plate or pipe flow). For such geometries the following relations based on experimental evidence are valid.

$$1. \quad \frac{u_o - u_b}{u_*} \approx 3.75 \quad (I.2)$$

(Reference 9 page 305)

where u_o is the maximum channel velocity

u_b is the bulk velocity

u_* the friction velocity.

$$2. \quad \frac{v_z}{u_0} \approx (1 - \xi)^{1/7} = e^{1/7 \ln(1-\xi)} \quad (I.3)$$

[Reference 55 page 75]

where

$$\xi = 1 - \frac{y}{\hat{y}} \quad (I.3a)$$

$$3. \quad k^{1/2} \approx 0.24 v_z (1 - \frac{u_b}{u_0}) e^{1.27\xi} \quad (I.4)$$

[Reference 2]

$$4. \quad (v_{rz}^T) \approx 0.07 u^* \hat{y} \quad (I.5)$$

[Reference 21]

In addition we approximate

$$\begin{aligned} 1.27 \xi + \frac{1}{7} \ln(1-\xi) &= 1.127\xi - \frac{\xi^2}{4} - \frac{\xi^3}{21} \\ &\approx 1.127\xi \end{aligned} \quad (I.6)$$

On the other hand according to our model (1-Eq Model)

$$v_{\theta z}^T \approx c_v c_L k^{1/2} \hat{y} \quad (I.7)$$

$$\therefore \overline{v_{\theta z}^T} = \int_0^1 c_v c_L k^{1/2}(\xi) \hat{y} d\xi \quad (I.8)$$

Since $c_v \approx 0.2$ $c_L \approx 0.4$

$$v_{\theta z}^T \approx 0.089 \int_0^1 k^{1/2}(\xi) d\xi$$

From (I.4) taking into consideration (I.2), (I.3) and (I.6) we find $k^{1/2}(\xi) \approx 0.9 u^* e^{1.427\xi}$ (I.9)

Substituting (I.9) for $k^{1/2}$ into Eq. (I.8) we obtain:

$$\overline{v_{\theta z}^T} \approx 0.133 u^* \quad (I.10)$$

which seems to be in agreement with (I.1)

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

TASK IIIA: Analytical and Experimental Investigation of Velocity and Temperature Fields (Y.B. Chen, Ralph Bennett)

The work in this task is carried on in parallel experimental and analytical efforts. The theoretical effort is concerned with employing numerical turbulence models (eg. TEACH-T¹, and VARR-II²) in predicting the velocity and temperature fields in the outlet plenum, and the experimental effort is focused upon validating these models, and with providing the data to guide their refinement for outlet plenum applications. These efforts are pursued in work concerned with steady state velocity-field measurements and calculations using water in a 1/15-scale FFTF outlet plenum model, and in work employing a Mach-Zehnder interferometer for turbulent temperature measurements using air in a similar model geometry.

III.1 Velocity-Field Measurements and Analysis (Y.B. Chen)

In the experimental part of this effort during the past quarter a new aluminum test section has been constructed to replace the previous plexiglas model. The new test section is much more rugged and flexible than the earlier one. As shown in Fig. III.1 it has the capability to permit the outlet plenum geometry to be

varied in a continuous range of configurations from a short-wide plenum to a narrow-tall plenum. It is also possible to vary the inlet nozzle and inlet shimmy configurations. In addition, the hydraulic loop was modified to include a 5 HP pump (in parallel with the original 1 HP pump) and a heat exchanger. The purposes of these changes are to obtain a higher flowrate, and to remove the pump-generated friction heat during the experiment operation in order to be able to maintain a constant flow Reynolds number. The new loop is shown in Fig. III.2. In order to minimize the corrosion of the test section, the distilled water and brass pipes are used in the entire loop.

As a part of the Laser Doppler Anemometer (LDA) system, an additional frequency downmixer was purchased from Thermo-System Inc. With this addition the LDA system is capable of making two-component velocity measurements simultaneously when operating in the reference beam mode. The schematic diagrams of the electronic system is shown in Fig. III.3.

The experimental setup is shown in Fig. III.4. The optical unit, laser and photomultiplier are mounted on a drilling machine table which can move in three mutually perpendicular directions. The test section sits on a fixed table. Movement of the drilling table will change the location of the probe volume in the test section, but no realignment of the optical unit or photomultiplier is necessary. Thus, it is possible to obtain data at different flow stations by simply cranking the drilling machine table.

During the past quarter all the new electronic equipment, hydraulic loop and test sections have been tested successfully. The new measurement system has been calibrated, and steady-state flow measurements have been started.

In the analytical effort, the TEACH-T code has been debugged and is ready for testing against experimental results. It has been used to predict the expected flow distribution in work presented previously.³ The VARR-II program has been tested as part of the ERDA network experiment at the Laboratory for Nuclear Studies. In this experiment the intention was to transfer the source program and input data to the Lawrence Berkeley Laboratory (LBL), to run it on their CDC 7600, and then to transfer the results back to MIT. At the beginning of the experiment, there occurred some difficulty in the speed and accuracy of transferring the file from MIT to LBL. When that problem was resolved, it was found that the transmitted program deck (old version of VARR-II) was not executable at LBL. In the next attempt the Science Applications Inc. (SAI) VARR-II file at LBL was used. In this attempt the transmitted input data file was found to be incorrect. Currently efforts are continuing to correct these problems.

III.2 Turbulent Temperature Measurements (Ralph Bennett)

Power spectral density measurements in the 1/15-scale FFTF outlet plenum model quarter with a refined analysis which has led to quantitative results. The experiments were carried out at a higher Reynolds number (about 20,000) than previously, with the substitution of a larger air blower. Several modifications were required to reduce the added pump noise which developed, and an inlet manifold vibration that developed. However, otherwise the flow geometry - employing co-flowing hot and cold air inlet streams - was the same as has been reported previously³ (see Fig. III.5); and the temperature measurement system is the Mach-Zehnder interferometer which has also been discussed previously.⁴

Fig. III.6 provides a rough picture of the frequency ranges of the dominant signals observed in the flow power spectral density (PSD) studies. While the flow turbulence surely produces temperature fluctuations with frequencies less than several hundred Hertz, they are masked by a hierarchy of sources of noise in the environment. The inlet manifold vibrations noted in the Figure were reduced by replacing the lightweight central inlet hose with a much stiffer "automotive" radiator hose. The pump noise has been reduced just recently by wrapping the 1/4 HP motor and "squirrel cage" blower in 8 to 12" of fiberglass insulation.

Two complete sets of PSD experiments at the same flow location are shown in Figs. III.7 and III.8 and in Figs. III.9 and III.10.

The spectrum analyzer was calibrated for both the positioning of frequency on the abscissa, and the display of relative logarithmic RMS fluctuation on the ordinate. Photographs of the RMS temperature fluctuation versus frequency have been smoothed-out by hand, and plotted as a mean-square fluctuation in Figs. III.7 and III.9. The traces marked 70 °F are background signals. They demonstrate how the upper limits of pump noise and manifold vibrations fall off rapidly above several hundred Hertz. These background traces are subtracted from each of the three curves above them. Each of the three resulting curves is normalized to unit area and replotted on Figs. III.8 and III.10.

All of the PSD curves are identical, within the accuracy of the technique. Thus, the inlet temperature upset is not driving any measureable instabilities in the turbulence. In effect, the temperature serves only to "color in" the turbulence.

The information foregone by normalizing the PSD curves to unit area was regained in a different experiment. The spectrum analyzer was stopped at 1500 Hz, and was used only to measure the value of the Fourier component at 1500 Hz. This frequency was chosen because it occurs at the largest ratio of signal to noise, and thus represents the most sensitive portion of the experiment. The output was smoothed for several seconds in an integrating circuit, and values were plotted against the applied temperature upset as shown in Fig. III.11. Two separate regressions of the

data are quoted in the Figure. They indicate that the RMS fluctuation (at 1500 Hz) increases very nearly linearly with the temperature upset.

References - II

1. A. D. Gosman, Listing of the TEACH-T Computer Program and Sample Output, Penn. State Univ. (1975).
2. J. L. Cook and P. I. Nakayama, VARR-II Computer Program for Calculating Time Dependent Turbulent Fluid Flows with Slight Density Variation, WARD-D-0106, Westinghouse Electric Co. (1975).
3. Neil E. Todreas and Michael W. Golay, Coolant Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients, ERDA Quarterly Report COO-2245-26, September 1, 1975 - November 30, 1975, Massachusetts Institute of Technology.
4. Neil E. Todreas and Michael W. Golay, Coolant Mixing in LMFBR Rod Bundles and Out Plenum Mixing Transients, ERDA Quarterly Report COO-2245-25, June 1, 1975 - August 31, 1975, Massachusetts Institute of Technology.

Fig. III.2 THE HYDRAULIC LOOP

Fig. III.3 LAYOUT OF ELECTRONICS

Fig. III.4 EXPERIMENTAL SETUP

Fig. III.5 Laminated Plexiglass test cell for interferometric temperature measurements

Fig. III.6 Characteristic frequency ranges for the various sources of interferometric signals

Fig. III.7 Smoothed curves of the photographs of the RMS fluctuation; plotted as mean-square fluctuation.

Fig. III.8 Three PSD curves from the data of Fig. 2

Fig. III.9 Smoothed curves of the photographs of the RMS fluctuation; plotted as mean-square fluctuation.

Fig. III.10 Three PSD curves from the data of Fig. 4.

Fig. III.11 Variation of the RMS fluctuation in the temperature signal at 1500 Hz with applied temperature upset. The data is modeled by the two different formulas.