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Results of the Advanced Diffusion-Dilution Mixing Test
Model as Applied to the Hobbed-Fin 19 Element Bundle Data

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ABSTRACT

Thorough investigation of results from all previous testing of Right-Left-Neutral fin geometries has led to the development of a mixing theory which postulates the existence of two distinct types of flow within the tricuspid. This advanced mixing theory predicts axial saline concentration distributions which agree well with experimental data. A mixing correlation has resulted from this theory which is empirically matched to several sets of experimental data. This mixing correlation is dependent only upon the geometry of the R-L-N finned element being considered.

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I. Introduction

A mathematical model has been developed to analyze the data from the saline-injection hydraulic mixing experiments. Previously developed models were unable to correlate with available data. The current model was designed upon a theoretical basis for the physical flow situation which is uniquely exhibited by the right-left-neutral finned geometry in the 19 element mixing test bundle. The advanced diffusion-dilution mixing test model combines rotational and diffusional flows, thus creating a mathematical mixing theory compatible with the derived experimental data.

II. Historical Background

The hydraulic mixing tests were begun by Atomics International to determine channel-to-channel cross flow for the ZrH Core Test Reactor. The initial tests (Reference 1) compared several mixing geometries: 1) no fins; 2) four fins (single wrap direction); 3) three fins (single wrap direction), 4) three fins (R-L-N wrap); and 5) twisted ribbons. A preliminary mathematical model based on tricuspid mass mixing was developed for the analysis of this test. The model was, however, unsuccessful in predicting meaningful saline concentrations for correlation with the experimental data. Single channel cross-flow calculations were thus used for the comparative mixing calculations.

These test results indicated the desirability of incorporating the right-left-neutral (R-L-N) fin geometry in all future reactor designs. Thus, all further tests were oriented toward determination of the interchannel mixing developed by the R-L-N fins. The tricuspid to tricuspid mass mixing model was improved for future tests (Reference 3). Experimental fins (manufactured of thin plastic strip which could be attached to neutral elements) were utilized with the existing bundle, and further mixing data was extracted (Reference 4). However, probe-to-probe crosstalk was discovered within the test setup electronics, and a limited amount of usable data was obtained from the test (Reference 4). This data confirmed the inapplicability of the analytical model to the experimental setup, in that correspondence between calculated and experimentally determined data points was very poor.

The final hydraulic testing of the R-L-N mixing system for the SPF Reactor was designed to provide greater amounts of more precise data than was obtained from any previous testing. The test included the utilization of: 1) hobbled fin elements; 2) 16 concentration probes per element; 3) shielded cable for probe linkage to electronics; 4) simultaneous saline injection in three channels to provide system symmetry; and 5) automated data handling coupled with computerized data processing. Details concerning these improvements are discussed in References 5, 6, 7 and 8.

The improved mixing test model developed from a careful study of the non-interacting data (no probe-to-probe crosstalk) from the plastic fin mixing test (Reference 4). The model was developed for applicability to the specific mixing system tested with the 19 element hobbled fin bundle. The theory is a simplified mathematical description of the complex flows occurring in the R-L-N mixing system.

III. Mathematical Model

A. System Description

A pictorial layout of the 19 element test bundle is shown in Figure 1. Fluid flow directions about the finned elements are indicated by arrows. The system utilized a "triple injection system" and the positions of the three matched saline injection units are indicated in the figure. Saline concentration probes are located on sixteen axial levels. The azimuthal positions of these lines of probes are shown on the element inner periphery. More than one peripheral position on a given element indicates rotation of that element between measurements.

B. Model Description

A pictorial of the model (in successive enlargements) is shown in Figures 2, 3 and 4. Note that incorporation of the triple injection method in the test system allows for modeling on an 8-fold symmetry. Thus a 45° sector provides all the detail necessary for a full bundle model. The model only considers four half-tricusps. Investigation of the data from the plastic finned mixing tests indicated that modeling of the

"return path" about the central element (see Figure 3) was unnecessary, in that no appreciable concentration from this return path is measured within the axial constraints of the test setup. Thus, the four half-tricusps are considered to be coupled with an infinite zero saline concentration sink.

As can be seen from Figure 3, two types of flow exist in each half-tricusp. The existence of two distinct flows is the theoretical basis for the advanced diffusion dilution model. "Rotational Flow" exists within an effective fin envelope determined by the geometry of the system and the effective height of the fins. "Rotational Flow", as its name implies, spirals about the finned elements in a clockwise or counterclockwise direction. An effective axial pitch (that distance in which the flow completes one revolution) is associated with this flow. As observed from early mixing experiments on R-L-N wire wrapped elements in SRE (Reference 9), this flow pitch is essentially infinite (no rotation) as the fluid enters the test bundle. The rotational flow is established as the fins interact with the fluid in the effective fin envelope. Thus, an entrance region exists in which the spiraling flow is converging toward an equilibrium axial to azimuthal velocity ratio. SRE observations indicate that this final ratio results in an axial flow pitch which is approximately two times the axial pitch of the wire wrap (the SRE "fins"). Within the SRE "entrance region", the effective rotational flow pitch was somewhat

less than four times the wire wrap pitch. These observations from the SRE mixing experiment serve to establish that rotational flow equilibrium exists, and significant slippage occurs within the effective fin envelope (see Figure 5).

"Diffusional Flow" is the second type of flow considered to exist within the half-tricuspid. In the diffusional section of the half-tricuspid, the average mass flow is in the axial direction only. A distinct boundary separates the rotational and diffusional flows. Mass transport is postulated to occur across this boundary. The transport mechanism is analogous to an eddy diffusivity phenomenon which is additionally perturbed by the presence of the rotating flow field generated by the R-L-N fins. It is thus the interaction between the "Rotational Flow" (the inter-channel transport mechanism) and the "Diffusional Flow" (the inner-channel transport mechanism), that defines the saline concentration distribution through the 19 element test bundle. This interaction is defined through a "normalized diffusion coefficient" which is a ratio between the average lateral velocity (or eddy transport velocity) and the average axial velocity.

C. Modeling Equations

Figure 4 illustrates the half-tricuspid division utilized in the current model. Thirty radial sectors (2° /sector) were used in each half-tricuspid. Each radial sector was divided into a rotational and

diffusional subchannel (unless the effective fin envelope intersected the tricuspid symmetry boundary --see Figure 4). Thus the model consisted of at most 60 sub-channels per half-tricuspid (30 rotational sub-channels and 30 or less diffusional sub-channels), or 240 sub-channels for the four half-tricuspids modeled.

Generalized equations were written for the rotational and diffusional subchannels (see Figure 6). Equations were developed to determine all geometrical factors appearing in these differential equations (based on dimensional input data). The entrance length effect was modeled as a simple decaying exponential factor which multiplied the effective axial flow pitch (see Figure 7). An equation was developed for the tricuspid-to-tricuspid mixing rate (lateral mass flow per unit axial mass flow per axial inch-- expressed in percent). This equation depends on geometrical input and rotational flow parameters only (see Figure 8).

An analog simulation program (IBM-Continuous System Modeling Program) was utilized to axially integrate the resultant 240 coupled linear differential equations. Eight thousand axial integration steps were employed to insure accuracy. All concentrations were normalized to unit saline injection, thus initial conditions were established as follows: 1) unit concentration in all injection half-tricuspid subchannels; 2) zero concentration in all other subchannels; and 3) zero concentration in both sinks. CRT plotting techniques were employed to simplify comparison of analytical and experimental data.

A listing of the geometrical and flow parameters necessary for a saline distribution simulation are detailed in Figure 9. Included in this list is the normalized azimuthal diffusion constant, which was included in the model for completeness. Determination of the effects of the azimuthal coupling terms was made on a typical simulation (over a wide range of azimuthal diffusion constant values - 0.0 to 1.0). However, negligible difference was seen over this wide range, because the rotational subchannel to diffusional subchannel coupling was large for all simulations of interest. Thus, as noted in Figure 9, this constant was assumed to be zero for all further simulations.

It should be noted that this model does not use the mixing factor as an input to the saline distribution simulations. Mixing is internally calculated by the model as an output dependent upon certain geometrical and flow parameters. Thus the model is iteratively used to determine the input parameter set which will best simulate the experimental data considered. The resultant mixing factor is specifically determined by this "best fit" input parameter set.

IV. Data Acquisition and Processing

Unprocessed digital data was received from the 19 element hobbled fin mixing test (Reference 8). Two fin heights were used in the mixing experiment: 1) nominal 30 mil fins; and 2) nominal 15 mil fins. The 30 mil fin data was received first and used to develop data reduction techniques.

Data was established at three Reynolds numbers (10000 ,15000, and 20000). Visual comparison of the unprocessed data revealed that no significant resolvable difference existed between these three data sets. This is an indication that a given "best fit" input parameter set for the simulation model is independent of Reynolds number, and that the mixing factor is thus independent of Reynolds number. However, the "true" diffusion factors are normalized to axial velocity (i. e. , Reynolds number), and thus are varying linearly with Reynolds number. The inner-channel transport phenomenon is Reynolds number dependent; the inter-channel transport phenomenon is not Reynolds number dependent. These assumptions having been made, it suffices to analyze data at only one Reynolds number (which was here chosen as 15000).

Data acquisition was limited (by the electronics) to 25 probes at any one time. Several sets of 25 data points each were thus taken at a given Reynolds number and their compatibility assured. The necessity to rotate certain of the instrumented elements during the test sequence (to obtain data from certain element-to-element gaps) caused perturbations in the output data set compatibility. These perturbations were additionally influenced by the positioning of the leading edge of the fins in reference to the injection gridplate hole. Though all fins began at the gridplate (in an element-to-element gap),

the saline injection solution first "saw" a "right" or "left" fin, thus obtaining a preferred rotational state.

The effects of such perturbations can be seen in Figure 10. The necessary locational nomenclature is given in Figure 11 (see also Figure 1). A simple method was devised to obtain a weighted average saline concentration for any given gap, independent of being "right" or "left" of the injection tricuspid. The method was based on certain data points which were common to most measurement sets. This unnormalized data was thus reduced to four axial saline concentration distributions. All data was then normalized to unit total concentration at that axial probe location where the injection exit gap (gap 1) measurement peaked. The final resultant concentration distributions for the 30 mil fin bundle are shown in Figure 12. (The gap naming technique is presented in Figure 11).

The results of applying this methodology to that data received from the 15 mil fin tests and the earlier plastic fin tests is plotted in Figures 13 and 14.

V. Theoretical to Experimental Correlation

The advanced diffusion dilution model was required to duplicate three concentration distribution data sets; 1) the 30 mil (nominal) hobbled-fin bundle; 2) the 15 mil (nominal) hobbled-fin bundle; and 3) the 20 mil (nominal) plastic fin bundle. The specific test setup dimensions are detailed in Figure 15.

The model was iteratively fitted to the 30 mil fin data, in that this test had provided the most detailed concentration distributions (all gaps showed concentration peaking within the test bundle). The five input parameters (see Figure 9) were varied over wide ranges of values, and a "best fit" simulation selection was made. The resultant theoretical concentration distributions and input parameter values are shown in Figure 16. A theoretical-experimental comparison is shown as Figure 17.

The true "uniqueness" of the "best fit" input parameter set cannot be rigorously demonstrated. It is pertinent, however, that each parameter was varied about its "best fit" value, with a resultant "poorer fit" to the experimental data. Additional checks were made on those parameters which affected the mixing factor calculation. Pairs of these parameters were varied inversely about their "best fit" values such that the mixing factor remained constant. Again, a "poorer fit" to the experimental data resulted.

The following postulates were made in order to extend this correlation to the two remaining data sets: 1) the thickness of the effective fin envelope varies linearly with the averaged fin height; 2) the normalized diffusion coefficient remains constant for a R-L-N finned bundle (with a circular fin envelope, i.e., non-scalloped); 3) the effective flow development entrance length varies inversely to the

average fin height; and 4) the axial flow pitch (initial and final values) varies linearly with the axial pitch of the fins. Applying these assumptions to the input data set resulted in a group of concentration distributions for the 15 mil and 20 mil fin test bundles. These curves (and associated parameter values) are shown as Figures 18 and 19. Comparison to the experimental curves (Figures 20 and 21) reveals that good agreement exists for the 15 mil hobbled fin data, while only fair agreement exists for the 20 mil plastic fin data. The latter "poorness of fit" is believed attributable to characteristics of the data acquisition system for this set of tests, and the relatively few data points available from this test.

VI. Mixing Correlation Development

Compilation of the assumptions of Section V, the specific test bundle dimensions of Figure 15, and the "best fit" input parameter set of Figure 17 provides the following empirical relations for input to the mixing correlation.

$$t_{\text{flow}} = 0.717 \times H_{\text{fin}}$$

$$P_{\text{flow, i}} = 3.64 \times P_{\text{fin}}$$

$$P_{\text{flow, f}} = 1.91 \times P_{\text{fin}}$$

$$Z_{\text{ent}} = 0.0663 / H_{\text{fin}}$$

where:

H_{fin} = Average Fin Height (in)

P_{fin} = Fin Axial Pitch (in)

Combining a standard equation for the area of a tricuspid (including a term for the fin cross sectional area) with the mixing equation of Figure 8, the following empirical mixing correlation for a R-L-N fin geometry results.

$$h_{mix} = \frac{236 P_{elem} H_{fin}}{P_{fin} (0.433 P_{elem}^2 - 0.393 D_{elem}^2 - W_{fin} H_{fin}) (1 + 0.91 e^{-45.2 H_{fin}^z})}$$

where :

P_{elem} = Element-Element Separation (in)

H_{fin} = Average Fin Height (in)

P_{fin} = Axial Pitch of Fins (in)

D_{elem} = Element Outer Diameter (in)

W_{fin} = Fin Width (horizontal Projection) (in)

z = Axial Distance into Bundle (in)

h_{mix} = Mixing Parameter (%/in)

Typical performance of this equation is demonstrated in Figure 22 for the 30 mil fin "best fit" input parameter set.

VII. Conclusions

A mixing theory has been developed for Right-Left-Neutral fin geometries which postulates the existence of two distinct types of flow within the tricuspid. This advanced diffusion-dilution mixing theory calculates axial concentration distributions which agree well with experimental results. First order approximations were used to extend the theory over several fin geometry dimensional variations, with continued good agreement to experimental results. A mixing correlation has resulted from the study which calculates tricuspid-to-tricuspid mixing as a function of several element geometrical constants.

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LEFT $\longleftrightarrow$ RIGHT
SYMMETRY LINE

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FIGURE 2
ADVANCED DIFFUSION-DILUTION MIXING TEST SECTOR

 ROTATIONAL SUBCHANNEL

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FIGURE 3

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ROTATIONAL FLOW PITCH WITH SLIPPAGE AT FINS

FIGURE 5

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FIGURE 6
GENERALIZED SUBCHANNEL EQUATIONS

$$\frac{dC_{m_2}}{dz} = \frac{1}{P_{flow} / n} (C_{m_1} - C_{m_2}) + \left(\frac{D_R}{V} \right) \left(\frac{L_{m_2-D_2}}{A_{m_2}} \right) (C_{D_2} - C_{m_2})$$

$$\begin{aligned} \frac{dC_{D_2}}{dz} = & \left(\frac{D_R}{V} \right) \left(\frac{L_{m_2-D_2}}{A_{D_2}} \right) (C_{m_2} - C_{D_2}) \\ & + \left(\frac{D_A}{V} \right) \left(\frac{L_{D_2-D_3}}{A_{D_2}} \right) (C_{D_3} - C_{D_2}) \\ & + \left(\frac{D_A}{V} \right) \left(\frac{L_{D_2-D_1}}{A_{D_2}} \right) (C_{D_1} - C_{D_2}) \end{aligned}$$

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FIGURE 6 (continued)

M_1, M_2, M_3	=	Rotational Subchannel Nomenclature
D_1, D_2, D_3	=	Diffusional Subchannel Nomenclature
C_{M_1}	=	Saline Concentration in Subchannel M_1 (etc)
C_{D_1}	=	Saline Concentration in Subchannel D_1 (etc)
P_{flow}	=	Axial Flow Pitch
n	=	# of Rotational Subchannels per Half-Tricuspid
D_R	=	Radial Diffusion Constant
V	=	Axial Average Velocity
D_R/V	=	Normalized Radial Diffusion Constant
D_A/V	=	Normalized Azimuthal Diffusion Constant
$L_{M_2-D_2}$	=	Width of Boundary Between Subchannels M_2 and D_2
A_{M_2}	=	Area of Subchannel M_2
$L_{D_2-D_3}$	=	Width of Boundary Between Subchannels D_2 and D_3
A_{D_2}	=	Area of Subchannel D_2

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FIGURE 7
AXIAL FLOW PITCH ENTRANCE EFFECT MODEL

$$P_{\text{flow}} = P_{\text{flow},f} + (P_{\text{flow},i} - P_{\text{flow},f}) e^{-3z/Z_{\text{ent}}}$$

where:

- P_{flow} = Axial Flow Pitch
- $P_{\text{flow},i}$ = Initial Axial Flow Pitch (on entrance to bundle)
- $P_{\text{flow},f}$ = Final Axial Flow Pitch (asymptotic value)
- z = Axial Distance into Bundle
- Z_{ent} = Effective Entrance Length (three e-folding)

$$Q_{\text{LATERAL}} = t_{\text{flow}} \times l_{\text{gap}} \times V_{\text{AXIAL}} \times \tan \theta \times 2$$

$$Q_{\text{AXIAL}} = A_{\text{tricusp}} \times V_{\text{AXIAL}}$$

$$\tan \theta = \frac{\frac{1}{6} \pi P_{\text{elem}}}{\frac{1}{6} P_{\text{flow}}}$$

Thus

$$h_{\text{mix}} = \frac{Q_{\text{LATERAL}}}{Q_{\text{AXIAL}}} / l_{\text{gap}}$$

$$h_{\text{mix}} = \frac{2 \pi t_{\text{flow}} P_{\text{elem}}}{A_{\text{tricusp}} P_{\text{flow}}} \times 100 \quad \%/\text{inch}$$

TRICUSP-TRICUSP MIXING RATE CALCULATION

FIGURE 8

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FIGURE 9

INPUT FOR ADVANCED DIFFUSION-DILUTION MODEL

Geometric Factors

- 1) D_{elem} - Element Outer Diameter
- 2) H_{fin} - Average Fin Height
- 3) W_{fin} - Fin Width (horizontal projection)
- 4) P_{elem} - Element-Element Separation

Modeling Flow Parameters

- 1) $P_{flow,i}$ - Initial Flow Pitch
- 2) $P_{flow,f}$ - Final Flow Pitch
- 3) t_{flow} - Effective Thickness of Flow Envelope
- 4) Z_{ent} - Effective Flow Development Entrance Length
- 5) (D_R/V) - Normalized Radial Diffusion Constant
- 6) (D_A/V) - Normalized Azimuthal Diffusion Constant (=0)

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FIGURE 10

UN-NORMALIZED, UNAVERAGED MIXING TEST DATA
30 MIL HOBBED FINS - REYNOLDS # = 15000

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FIGURE 11

CONCENTRATION PROBE LOCATION NOMENCLATURE

● Saline Injection Point

○ Concentration Probe

→ Flow Direction

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FIGURE 12

REYNOLDS # = 15000

NORMALIZED MIXING TEST DATA - 30 MIL FINS

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FIGURE 13

NORMALIZED MIXING TEST DATA - 15 MIL FINS - REYNOLDS # = 15000

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FIGURE 14

REYNOLDS # - 15000

NORMALIZED MIXING DATA - 20 MIL PLASTIC FINS

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FIGURE 15
SPECIFIC TEST GEOMETRY CHARACTERISTICS

<u>Characteristic</u>	<u>30 MIL FINS</u>	<u>15 MIL FINS</u>	<u>20 MIL FINS</u>
Fin Type	Hobbed	Hobbed	Plastic Tape
# of Fins	Three	Three	Three
Element Outer Diam*	0.642	0.657	0.560
Elem-Elem Separation	0.670	0.670	0.584
Actual Fin Height	0.0265	0.0115	0.0180
Fin Width	0.070	0.070	0.050
Axial Fin Pitch	5.50	5.50	4.00
Finned Length	16.0	16.0	16.0

* All Dimensions in Inches

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FIGURE 16

THEORETICAL CONCENTRATION DISTRIBUTIONS - 30 Mil Pins

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FIGURE 17

THEORETICAL - EXPERIMENTAL COMPARISON

30 MIL FIN DATA

"Best Fit" Input Parameter Set

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FIGURE 18

THEORETICAL CONCENTRATION DISTRIBUTIONS - 15 Mil Fins

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FIGURE 19

THEORETICAL CONCENTRATION DISTRIBUTIONS - 20 Mil Plastic Fins

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FIGURE 20

THEORETICAL - EXPERIMENTAL COMPARISON

15 MIL FIN DATA

"Best Fit" Input Parameter Set

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FIGURE 22

TYPICAL AXIAL MIXING PARAMETER VARIATION

30 Mil Hobbed Fins - "Best Fit" Input Parameters