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EVALUATION OF THE RELAP5/MOD3 MULTIDIMENSIONAL COMPONENT MODEL

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ABSTRACT

Accurate plenum predictions, which are directly related to the mixing models used, are an important plant modeling consideration because of the consequential impact on basic transient performance calculations for the integrated system. The effect of a plenum (e.g., reactor vessel downcomer plus inlet, reactor outlet, steam generator inlet and outlet, etc.) is a time shift between inlet and outlet temperature changes to the particular volume. Perfect mixing, where the total volume interacts instantaneously with the total inlet flow, does not occur because of effects such as inlet/outlet nozzle jetting, flow stratification, nested vortices within the volume (which reduce the effective mixing volume) and the general three-dimensional velocity distribution of the flow field. The time lag which exists between the inlet and outlet flows impacts the predicted rate of temperature change experienced by various plant system components and this impacts local component analyses which are affected by the rate of temperature change. This study includes a comparison of two-dimensional plenum mixing predictions using CFD-FLOW3D (FLOW3D), RELAP5/MOD3 and perfect mixing models. Three different geometries (flat, square and tall) are assessed for scalar transport times using a wide range of inlet velocity and isothermal conditions. In addition, the three geometries were evaluated for low flow conditions with the inlet flow experiencing a large step temperature decrease. These cases would be indicative of those causing thermal flow stratification which should influence the plenum thermal mixing performance, particularly at lower velocities. A major conclusion from this study is that the RELAP5/MOD3 multidimensional component model appears to be adequately predicting plenum mixing for a wide range of thermal-hydraulic conditions representative of plant transients.

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1.0 INTRODUCTION

Accurate plenum predictions, which are directly related to the mixing models used, are an important plant modeling consideration because of the consequential impact on basic transient performance calculations for the integrated system. The effect of a plenum (e.g., reactor vessel downcomer plus inlet, reactor outlet, steam generator inlet and outlet, etc.) is a time shift between inlet and outlet temperature changes to the particular volume. "Perfect mixing", where the total volume interacts instantaneously with the total inlet flow, does not occur because of effects such as inlet/outlet nozzle jetting, flow stratification, nested vortices within the volume (which reduce the effective mixing volume) and the general three-dimensional velocity distribution of the flow field. The time lag which exists between the inlet and outlet flows impacts the predicted rate of temperature change experienced by various plant system components and this impacts local component analyses which are affected by the rate of temperature change. This includes structural analyses on components within and downstream of the plenum and the nuclear kinetic analyses of the core where the reactivity feedback associated with temperature change is impacted. Thus, in general, accurate modeling capability of the mixing phenomena associated with various components around the plant is needed to have an accurate representation of the integrated system transient response.

Figure 1 provides an example of typical flow patterns for an idealized plenum configuration. The nested vortices (forming recirculation regions) shown in opposite corners of the plenum result in a loss of effective mixing volume. The flow tends to take the minimum resistance of the shorter path as indicated by the larger velocity vectors for this portion of the flow field. A "perfect mixing" model would assume each increment of coolant mixes instantaneously and uniformly with all the coolant in the plenum. As can be noted from the flow field depicted by Figure 1, this would be a rather poor assumption for this particular example.

This study includes a comparison of plenum mixing predictions using CFD-FLOW3D (FLOW3D), RELAP5/MOD3 and perfect mixing models. Three different geometries are assessed for scalar transport times using a wide inlet velocity range and isothermal conditions. In addition, the three geometries were evaluated for low flow conditions with the inlet flow experiencing a large step temperature decrease. These cases would be indicative of those causing thermal flow stratification which should influence the plenum thermal mixing performance particularly at lower velocities. The colder fluid would tend to significantly mitigate the mixing because of the buoyancy effects forcing it to settle to the bottom of the plenum.

One of the objectives of the comparisons is to assess the predictive capabilities of the RELAP5/MOD3 multidimensional component model which has recently been added to the code for performing these types of analyses [Reference (a)]. In addition, the studies provide trends to help guide modeling requirements for the geometries and conditions evaluated. Conditions and geometries which result in wide variations between the predictive methods indicate those potentially needing improved modeling detail and accuracy.

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FIGURE 1: TYPICAL EXAMPLE OF 2-D FLOW PATTERN FOR IDEALIZED MIXING PLENUM

2.0 PLENUM GEOMETRIES AND CONDITIONS USED IN ASSESSMENT

Figure 2 shows a schematic of the two-dimensional plenum model used for the studies. In all cases, the centerlines of the inlet and outlet nozzles were placed at 20% and 80% of the plenum height, respectively. Three geometries were considered with various width (W) to height (H) ratios (W/H). As indicated, $W/H = 2$ was used to typify a "flat plenum", $W/H = 1$ was used to typify a "square plenum" and $W/H = 0.5$ was used to typify a "tall plenum".

Table 1 provides a summary of the various cases evaluated. All three geometries were assessed for isothermal flow (500°F, 2000 psig) at inlet velocities of 30, 10 and 0.5 feet per second. In addition, all three geometries were analyzed for a 90°F step decrease in inlet temperature with an inlet velocity of 0.1 feet per second. This latter set of conditions was selected to exemplify the effects of the flow stratification on the flow mixing. The Richardson number (Ri) is the ratio of buoyancy to dynamic forces acting in the plenum. A Richardson number of 1.0 indicates a propensity for flow stratification. Cases 10, 11 and 12 in Table 1 have a Richardson number of over 50 and thus each case should have strong stratification phenomena superimposed into the mixing process.

FIGURE 2: PLENUM GEOMETRIES EVALUATED

PLENUM DEFINITION

GEOMETRIES

$\frac{W}{H} = 2$ ($W = 20D$, $H = 10D$), FLAT PLENUM

$\frac{W}{H} = 1$ ($W = 10D$, $H = 10D$), SQUARE PLENUM

$\frac{W}{H} = 0.5$ ($W = 5D$, $H = 10D$), TALL PLENUM

TABLE 1: SUMMARY CASES EVALUATED

Case	Width	Height	Description	Inlet Vel. (fps)	Conditions
1	20D	10D	Flat	30.0	Isothermal
2	20D	10D	Flat	10.0	Isothermal
3	20D	10D	Flat	0.50	Isothermal
4	10D	10D	Square	30.0	Isothermal
5	10D	10D	Square	10.0	Isothermal
6	10D	10D	Square	0.50	Isothermal
7	5D	10D	Tall	30.0	Isothermal
8	5D	10D	Tall	10.0	Isothermal
9	5D	10D	Tall	0.50	Isothermal
10	20D	10D	Flat	0.10	$\Delta T = -90^{\circ} \text{ F}$
11	10D	10D	Square	0.10	$\Delta T = -90^{\circ} \text{ F}$
12	5D	10D	Tall	0.10	$\Delta T = -90^{\circ} \text{ F}$

NOTE: D = 1.0 ft (current evaluation)

3.0 PLENUM MIXING MODELS COMPARED

Plenum mixing predictions using a perfect mixing model, a FLOW3D model and a RELAP5/MOD3 model are compared in this study. Key features of these models are described in this section.

3.1 PERFECT MIXING MODEL

A perfect mixing model assumes that each incoming increment of fluid mixes instantaneously and uniformly with all the coolant in the plenum. If the temperature of the incoming coolant changes in a stepwise fashion by an amount, ΔT_i , the transient outlet temperature response, $\Delta T_o(\tau)$, is given by

$$\frac{\Delta T_o(\tau)}{\Delta T_i} = 1 - \exp\left(-\frac{Q}{V} \tau\right)$$

Where

- Q = volumetric flow rate
- V = plenum volume
- τ = time since step inlet temperature change

With this type of one-dimensional model, two and three-dimensional effects such as nested vortexing flow regions and stratified fluid layers are assumed to have negligible influence on the transient outlet temperature.

The effective perfect mixing time constants, V/Q , for the three geometries and the four velocities considered in Table 1 are

Table 2: Perfect Mixing Time Constants

Plenum Geometry	Perfect Mixing Time Constant, V/Q , (secs.)			
	0.1 fps	0.5 fps	10 fps	30 fps
Tall	500	100	5	1.7
Square	1000	200	10	3.4
Flat	2000	400	20	6.8

For the conditions studied, it should be noted that a wide range of time constants were assessed for the three geometries. These ranges were selected to encompass cases with high to low degrees of turbulence influencing the mixing process. The shorter time constants, associated with the higher inlet velocities (e.g., 30 fps) would have the larger turbulent mixing for the same geometry.

3.2. FLOW3D MODEL

FLOW3D [Reference (b)] is a computational fluid dynamics (CFD) computer code which was developed by the United Kingdom Atomic Energy Authority (UKAEA), principally at the Harwell Laboratory in England. It is a general purpose computer program which uses the finite volume approach to simulate many classes of incompressible fluid flows. Turbulent mixing was incorporated using a standard $k-\epsilon$ model. The noding structure used consisted of a 40 x 40 grid for the Figure 2 plenum cross section. This resulted in a 6 inch grid subdivision for the 20 foot dimension, a 3 inch grid subdivision for the 10 foot dimension and 1.5 inch grid subdivision for the 5 foot dimension for the various Table 1 cases.

3.3 RELAP5/MOD3 MODEL

The RELAP5/MOD3 computer code is a light water reactor transient analysis code developed for the U.S. Nuclear Regulatory Commission (NRC) by EG&G Idaho, Inc. at Idaho National Engineering Laboratory (INEL). A recent version of the code has been developed by INEL [References (a) and (c)] with an additional capability of allowing multidimensional modeling of plant system components. In particular, this new capability allows improved modeling of phenomena associated with plenum fluid mixing. The model has a similar approach to solving the basic conservation equations in three dimensions as FLOW3D (Section 3.2) but does not include the capability of modeling turbulent mixing (which was modeled using the standard $k-\epsilon$ type model in FLOW3D for this study). One of the objectives of this study was to assess the impact of neglecting the turbulent mixing relative to plenum mixing predictions for the conditions considered in this study. The noding structure used 12 inch x 12 inch nodes for all of the Table 1 evaluations. However, some studies termed "fine mesh" had the grid dimension decreased to half this size (except for the nozzle elevations where the 12 inch dimension was maintained so that both the fine and coarse mesh studies have only a single node representing the nozzle inlet/outlet cross-sections).

4.0

COMPARISON OF RESULTS

Figures 3 to 16 show results predicted with FLOW3D, RELAP5/MOD3 (indicated as MULTID) and the perfect mixing model for the Table 1 conditions. The transient variation in scalar concentration at the outlet nozzle is shown by Figures 3 to 11 for a step change in concentration at the inlet nozzle. This scalar concentration trace does not affect the solution since it corresponds to the temporal variation in concentration of non-buoyant, inviscid dye injected at the inlet nozzle. Some observations that can be made by comparing the results include:

- All three predictive methods (for isothermal Cases 1 to 9 shown by Figures 3 to 11, respectively) exhibit good agreement for all three geometries at the higher velocities. Differences increase from about 10% at 30 fps to over 200% (for portions of the transient) at 0.5 fps.
- The largest differences among the three predictive methods (for isothermal Cases 1 to 9) occurred for the flat geometry and lowest velocity of Case 3 (Figure 5).
- Flow stratification effects have a significant impact on the mixing predictions as noted by comparison of the Case 10, 11 and 12 results shown by Figures 12, 13 and 14, respectively. Results from Cases 10 and 11 are shown only for the RELAP5/MOD3 and the perfect mixing models. Case 12 shows the predictions for all three models. Because of the good agreement between FLOW3D and RELAP5/MOD3 found for this tall plenum case (which would be the most severe geometry for these conditions), the FLOW3D analyses were not performed for the less severe Case 10 and 11 conditions (another deciding factor was that the Case 12 FLOW3D analyses took about seven hours on the Cray C90 computer compared to RELAP5/MOD3 which took less than five minutes).
- Cases 1 to 3 (flat plenum) and Cases 7 to 9 (tall plenum) were evaluated with and without a turbulent mixing model (i.e., $k-\epsilon$ model) using FLOW3D. The cases without turbulent mixing would be consistent with the RELAP5/MOD3 type of model which only includes the molecular viscosity in the effective viscosity term of the momentum equation. These results are given in Figure 15. As can be noted, the results are reasonably close which indicates that the mixing flow fields are inertia dominated rather than viscous dominated.
- Cases 2, 3 and 12 for the flat plenum were reanalyzed with a fine mesh RELAP5/MOD3 model described in Section 3.3. These predictions are superimposed on Figures 4, 5 and 12 and shown by Figures 16, 17 and 18, respectively. Only small changes in the RELAP5/MOD3 predictions were found.

5.0 SUMMARY OF RESULTS AND CONCLUSIONS

The following conclusions were derived from a review of the Section 4.0 predicted results for the twelve cases in Table 1.

- All three predictive methods (for isothermal Cases 1 to 9) exhibit good agreement for all three geometries at the higher velocities. Differences increase from about 10% at 30 fps to over 200% (for portions of the transient) at 0.5 fps.
- The largest differences between the three predictive methods (for isothermal Cases 1 to 9) occurred for the flat geometry and lowest velocity of Case 3.
- Cases 1 to 3 (flat plenum) and Cases 7 to 9 (tall plenum) were evaluated with and without a turbulent mixing model (i.e., $k-\epsilon$ model) using FLOW3D. The cases without turbulent mixing would be consistent with the RELAP5/MOD3 type of model. As can be noted, the results are reasonably close which indicates that the mixing flow fields are inertia dominated rather than viscous dominated.

Major conclusions from this study relative to the RELAP5/MOD3 model are:

- The RELAP5/MOD3 model appears to adequately predict plenum turbulent mixing for higher velocity conditions.
- At lower inlet velocity conditions (e.g., the 0.5 feet per second of Cases 3, 6, and 9), the RELAP5/MOD3 model has larger differences with the FLOW3D predictions. However, even for these conditions the comparisons are reasonably good as shown by the various comparison plots. The combination of low flow with thermal stratification superimposed was found to result in good agreement between RELAP5/MOD3 and FLOW3D, but large differences were found relative to predictions from a perfect mixing model which is often used in plant analysis computer codes. A comparison of the predictions by the three methods is given by Figure 14. Figure 19 shows an example of the FLOW3D prediction of the progression of thermal stratification for the tall plenum geometry of Case 12. For these type conditions, it is recommended that a more detailed check of the RELAP5/MOD3 model predictions be performed with a CFD code such as FLOW3D for the actual plant geometry and conditions that are being analyzed even though good agreement was found for this particular study. Figure 14 shows the deficiency of the perfect mixing model for the low flow conditions with thermal stratification occurring.
- Indications from this study are that the RELAP5/MOD3 model will be found to adequately predict the transient mixing performance of the various plena in the primary heat transport system, even for conditions indicative of the more severe design basis transients. The results show that the flow mixing fields are generally inertia dominated rather than viscous dominated and thus the lack of a turbulent mixing model in the RELAP5/MOD3 model does not have a significant effect on the predicted mixing for the cases studied.

6.0 REFERENCES

- a. K. E. Carlson, V. A. Mousseau and W. L. Weaver III, "Theory Manual for the RELAP5/NPR Code," HWR-D26225-14, EG&G Idaho, Inc., 1992
- b. A. D. Burns, N. S. Wilkes, I. P. Jones, and J. R. Kightley (1986), FLOW3D: body-fitted coordinates, AERE-R 12262.
- c. "RELAP5/MOD3 Code Manual," NUREG/CR-5535 (EG&G-2596), (DRAFT) June 1990.

FIGURE 3

CASE 1 FLAT PLENUM $V_{in} = 30.$ fps

FIGURE 4

CASE 2 FLAT PLENUM $V_{in} = 10.$ fps

FIGURE 5
CASE 3 FLAT PLENUM $V_{in} = 0.5$ fps

FIGURE 6

CASE 4 SQUARE PLENUM $V_{in} = 30. \text{ fps}$

FIGURE 7

CASE 5 SQUARE PLENUM $V_{in} = 10. \text{ fps}$

FIGURE 8

CASE 6 SQUARE PLENUM $V_{in} = 0.5$ fps

FIGURE 9

CASE 7 TALL PLENUM $V_{in} = 30$. fps

FIGURE 10

CASE 8 TALL PLENUM $V_{in} = 10$. fps

FIGURE 11

CASE 9 TALL PLENUM $V_{in} = 0.5$ fps

FIGURE 12

CASE 10 FLAT PLENUM $V_{in} = 0.1$ fps, Temp. Decrease

FIGURE 13

CASE 11 SQUARE PLENUM $V_{in} = 0.1$ fps, Temp. Decrease

FIGURE 14

CASE 12 TALL PLENUM $V_{in} = 0.1$ fps, Temp. Decrease

FIGURE 15: EFFECT OF TURBULENT MIXING ON TALL AND FLAT PLENUM PREDICTIONS

FIGURE 16. Case 10 with Additional Results for Fine Mesh RELAP5/MOD3 Model

CASE 102 FLAT PLENUM $V_{in} = 10.$ fps

FIGURE 17. Case 10 with Additional Results for Fine Mesh RELAP5/MOD3 Model

CASE 103 FLAT PLENUM $V_{in} = 0.5$ fps

FIGURE 18. Case 10 with Additional Results for Fine Mesh RELAP5/MOD3 Model
CASE 112 TALL PLENUM $V_{in} = 0.1$ fps, Temp. Decrease

FIGURE 19. FLOW3D Transient Predictions for Case 12 (Low Flow/Stratified Plenum)