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THE APPLICATION OF VOLUME-WEIGHTED SKEW-UPWIND DIFFERENCING TO THERMAL AND FLUID MIXING IN THE COLD LEG AND DOWNCOMER OF A PWR

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Upwind differencing has been the most common numerical scheme used in computational fluid flow and heat transfer in past years. However, the numerical diffusion induced by the use of upwind differencing can be significant in problems involving thermal mixing.[1,2] Thermal and fluid mixing in a pressurized water reactor during high pressurized coolant injection is a typical example where numerical diffusion is significant. An improved volume-weighted skew-upwind differencing is used here to reduce numerical diffusion without overshooting or undershooting which is the major defect of original skew-upwind differencing proposed by Raithby.[3,4] The basic concept of volume-weighted skew-upwind differencing is shown in Fig. 1. The flux from the west face in the two-dimensional case is interpolated as

$$\phi_w = \frac{A_1}{(A_1 + A_2)} \phi_1 + \frac{A_2}{(A_1 + A_2)} \phi_2 \qquad (1)$$

instead of ϕ_1 alone. A_1 and A_2 are the weighting areas for two different fluxes ϕ_1 and ϕ_2, respectively. The weighting area depends on the direction of the flow, $\vec{V}$. More complete information is given in Ref. (5). Our computations were performed using COMMIX-1B, an extended version of the COMMIX-1A.[6]

The experiment analyzed here is test No. 1 of the SAI experiment.[7] A simple rectangular geometry is used. The ratio of the loop flow to the HPI flow is 10.6 to 1 and the temperatures of the HPI flow and the loop flow are maintained at 17°C and 70°C, respectively. A simple turbulence model, instead of k-ε turbulence model, is used here to demonstrate the sole effect of skew-upwind differencing. An effective turbulent viscosity and conductivity are used throughout the computational domain.

The temperature distribution at time=256 seconds, after the initiation of the high pressurized coolant injection, is shown in Fig. 2. The experimental data from SAI[7] and the numerical results using upwind differencing also are shown in Fig. 2. Liu et al.[8] performed similar simulation on test No. 1, but different trends of the temperature profile in the cold leg were observed due to the difference in modeling the HPI injection; their results are not shown in Fig. 2. Near the injector, due to the small Froude number ($Fr_{HPI} = 0.004$) and high Reynolds number ($Re = 3.4 \times 10^4$), the cold fluid stays on top of the hot fluid, i.e., the mixing is small. Figure 2 shows that the penetration of the cold fluid by using upwind differencing is deeper than that by using volume-weighted skew-upwind differencing due to the effect of numerical diffusion. Further downstream in the cold leg, cold fluid tends to penetrate the bottom of the cold leg. The results of using upwind differencing show that the temperature profile is nearly uniform, whereas the experimental data showing stable thermal stratification was predicted by using volume-weighted differencing. At the entrance to the downcomer, another buoyancy effect was observed. Hot stagnant fluid at the top of the downcomer was sucked back into the cold leg resulting in significantly more stable thermal stratification in this entrance region than upstream locations. The results of using upwind differencing also illustrate this trend, but the maximum temperature difference is small ($\Delta T = 0.6$°C) when compared to the results of using volume-weighted skew-upwind differencing scheme ($\Delta T = 2.0$°C). In both schemes, cold fluid remains at the bottom of the cold leg, which is different from the experimental data.

In the primary side of the downcomer, cold fluid will impinge directly on the wall, resulting in an overcooling behavior generally referred to as "thermal shock". Our computation by using volume-weighted skew-upwind differencing, indicates that cold fluid does hit the wall of the downcomer although the temperature is not as cold as the experimental observation. The discrepancy between our computation and the experiment may be due to the heat loss in the experiment.[7,8]

A comparison of the calculated and experimental temperature profiles during the transient in the vertical centerline of the cold leg is shown in Fig. 3. Thermocouples L44 through L49 represent the temperature profiles from the top to the bottom of the cold leg. The quenching behavior, as indicated by the thermocouple readings near the bottom of the cold leg (L48 and L49), is very pronounced between 40 to 60 seconds after the initiation of high pressurized coolant injection. If the quenching is severe, "thermal shock" will occur. The quenching is slightly earlier for thermocouple L44 in our computation than in the experiment, but the agreement is very good for the rest of the thermocouples.

In conclusion, numerical diffusion is an important factor to be considered in the analysis of thermal shock. The newly implemented volume-weighted skew-upwind differencing scheme eliminates the bulk of the numerical diffusion. Analysis based on this new scheme improve significantly the agreement with the experimental data. Further refinements of the method are underway at ANL.

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$$\phi_w = \frac{A_1}{(A_1 + A_2)}\phi_1 + \frac{A_2}{(A_1 + A_2)}\phi_2$$

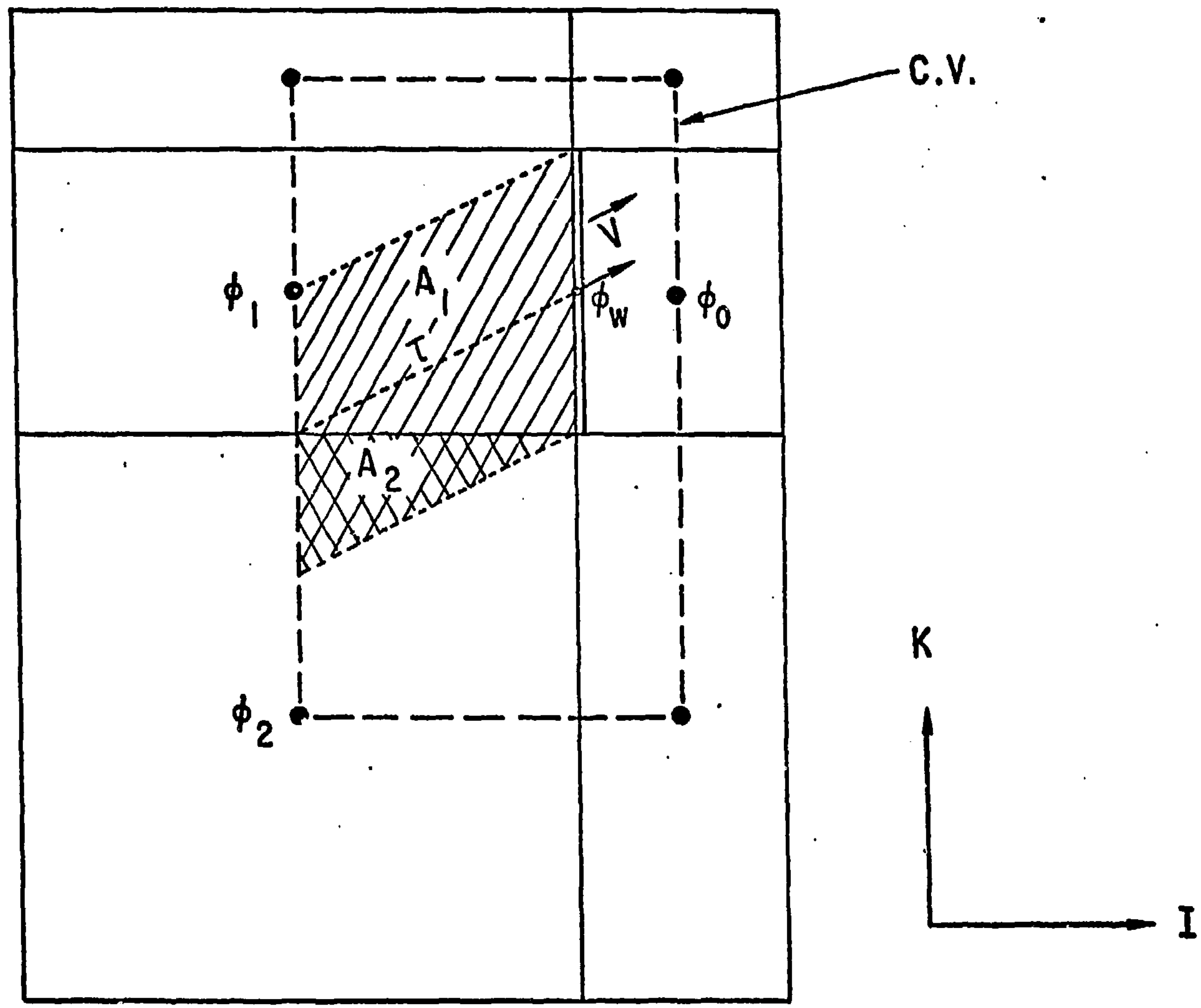

FIG. 1 CONCEPT OF VOLUME-WEIGHTED SKEW-UPWIND SCHEME

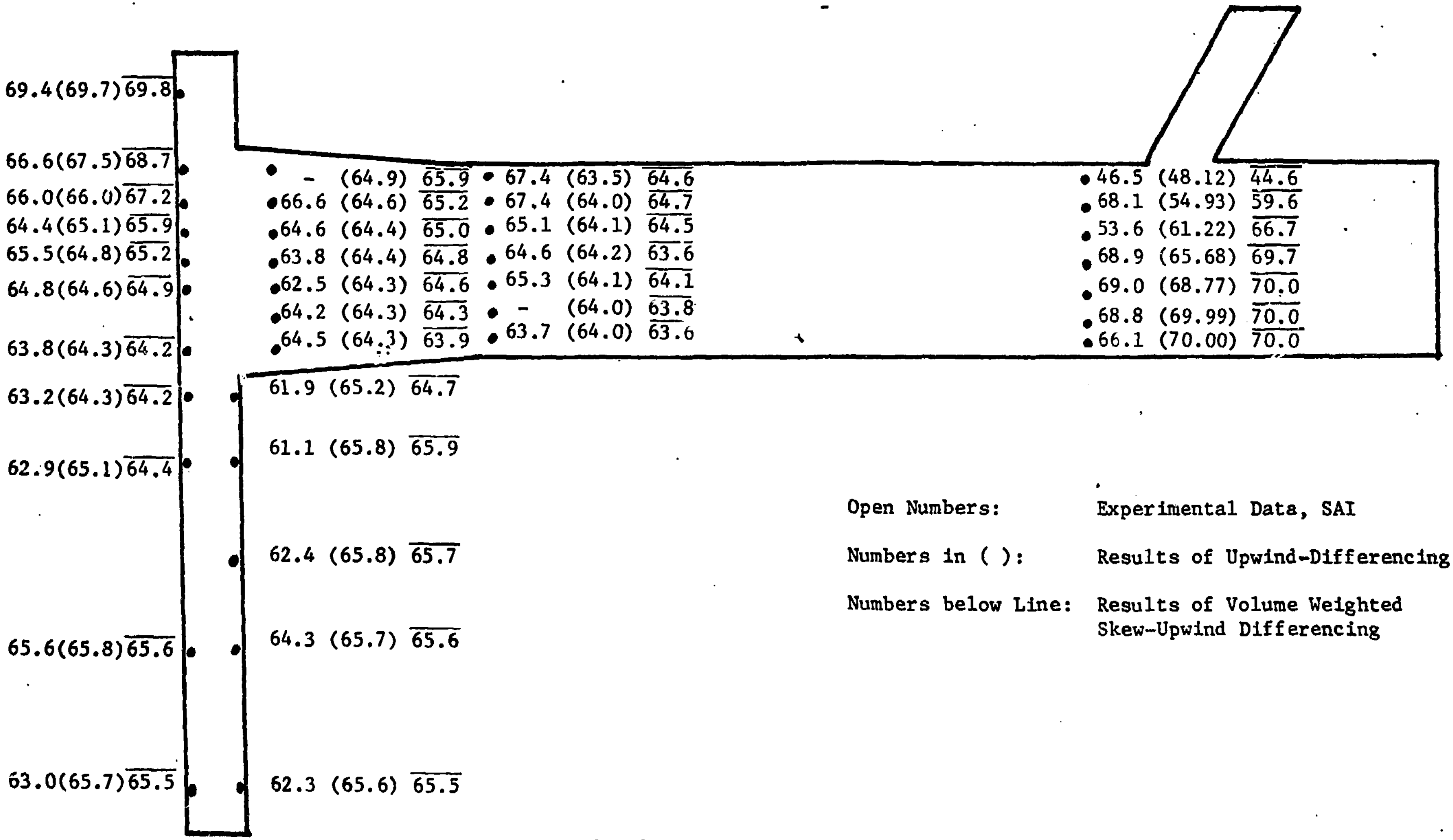

Fig. 2. Temperature distribution for SAI test No. 1 at t=256 sec. after high pressurized coolant injection at y=0 phase centerline).

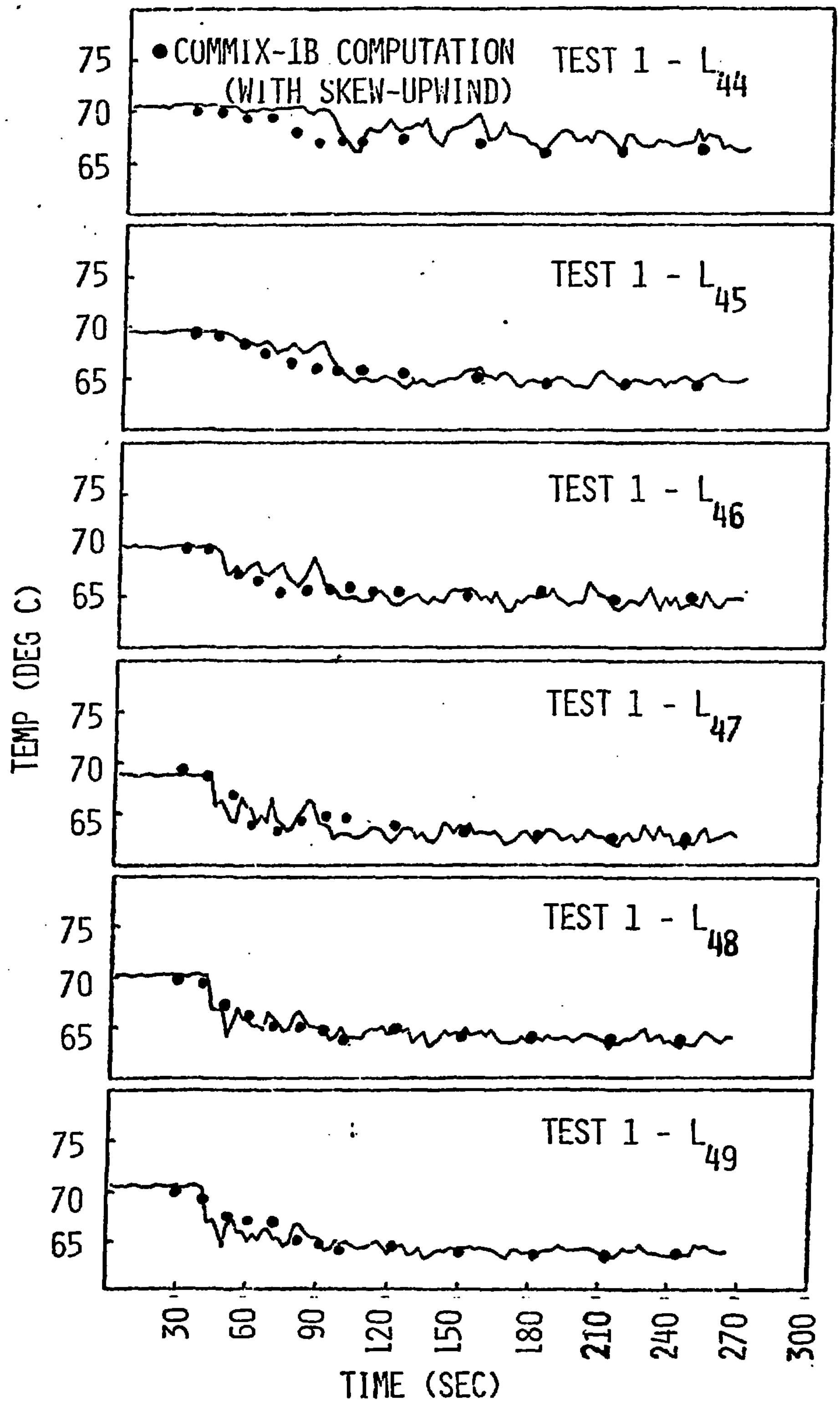

FIG. 3 VERTICAL CENTERLINE PROFILE OF TRANSIENT TEMPERATURES IN THE COLD LEG AT THE ENTRANCE TO THE DOWNCOMER - TEST 1.