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HYDRA-II: A Hydrothermal Analysis Computer Code

Volume I

Equations and Numerics

April 1987

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**Pacific Northwest Laboratory
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HYDRA-II: A HYDROTHERMAL ANALYSIS COMPUTER CODE
VOLUME I
EQUATIONS AND NUMERICS

R. A. McCann

April 1987

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ABSTRACT

HYDRA-II is a hydrothermal computer code capable of three-dimensional analysis of coupled conduction, convection, and thermal radiation problems. This code is especially appropriate for simulating the steady-state performance of spent fuel storage systems. The code has been evaluated for this application for the U.S. Department of Energy's Commercial Spent Fuel Management Program.

HYDRA-II provides a finite difference solution in Cartesian coordinates to the equations governing the conservation of mass, momentum, and energy. A cylindrical coordinate system may also be used to enclose the Cartesian coordinate system. This exterior coordinate system is useful for modeling cylindrical cask bodies.

The difference equations for conservation of momentum are enhanced by the incorporation of directional porosities and permeabilities that aid in modeling solid structures whose dimensions may be smaller than the computational mesh. The equation for conservation of energy permits modeling of orthotropic physical properties and film resistances. Several automated procedures are available to model radiation transfer within enclosures and from fuel rod to fuel rod.

The documentation of HYDRA-II is presented in three separate volumes. This volume, Volume I - Equations and Numerics, describes the basic differential equations, illustrates how the difference equations are formulated, and gives the solution procedures employed. Volume II - User's Manual contains code flow charts, discusses the code structure, provides detailed instructions for preparing an input file, and illustrates the operation of the code by means of a model problem. The final volume, Volume III - Verification/Validation Assessments, presents results of numerical simulations of single- and multiassembly storage systems and comparisons with experimental data.

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1.0 INTRODUCTION

Implementation of spent fuel dry storage systems may be required in the late 1980s because several at-reactor storage basins will attain maximum capacity (DOE 1985). The Nuclear Waste Policy Act of 1982 (NWPAA) assigns the U.S. Department of Energy (DOE) the responsibility for assisting utilities with their spent fuel storage problems. One of the provisions of the NWPAA is that DOE shall provide generic research and development of alternative spent fuel storage systems to assist utilities in their licensing activities.

One of the important requirements for storage systems is that they dissipate heat while maintaining the temperature of the stored materials below established limits. The thermal performance of a storage system can be assessed by a comprehensive testing program. Such testing programs are typically time-consuming and expensive. Analysis tools (e.g., computer codes), while not intended to entirely supplant testing methods, can perform a valuable service. Appropriately qualified computer codes can provide predictions of thermal performance as a function of system design and operating conditions. Moreover, when tests are to be performed, computer codes can help select test conditions, spent fuel decay heat generation rates, and instrumentation placements, as well as aid in interpreting test data.

HYDRA-II is a computer code for heat transfer and fluid flow analysis. An enhanced version of HYDRA-I (McCann 1980), it is a member of the HYDRA family of general purpose codes collectively capable of transient three-dimensional analysis of coupled conduction, convection, and radiation problems. This current version is especially appropriate for simulating the steady-state performance of spent fuel storage systems of current interest. A specialized version was deemed appropriate for two reasons: 1) it provides a reasonable level of generality for most potential users without the unwelcome burden of excess complexity and cost, and 2) it permits public availability of the code in a timely fashion.

The documentation of HYDRA-II is presented in three separate volumes. This volume, Volume I - Equations and Numerics, describes the basic differential equations, illustrates how the difference equations are formulated, and

gives the solution procedures employed. The second volume, Volume II - User's Manual, contains code flow charts, discusses the code structure, provides detailed instructions for preparing an input file, and illustrates the operation of the code by means of a model problem. The final volume, Volume III - Verification/Validation Assessments, presents results of numerical simulations of single- and multiassembly storage systems and comparisons with experimental data.

2.0 CODE OVERVIEW

HYDRA-II provides a finite difference solution in Cartesian coordinates to the equations governing the conservation of mass, momentum and energy. A cylindrical coordinate system may also be used to enclose the Cartesian coordinate system. This exterior coordinate system is useful for modeling cylindrical cask bodies. When both coordinate systems are invoked, the code will automatically align the two systems and enforce conservation of energy at their interface.

The difference equations for conservation of momentum are enhanced by the incorporation of directional porosities and permeabilities that aid in modeling solid structures whose dimensions may be smaller than the computational mesh. The specification of in-flow and out-flow boundary conditions has been eliminated as appropriate for sealed storage systems. The equation for conservation of energy permits modeling of orthotropic physical properties and film resistances. Several automated procedures are available to model radiation transfer within enclosures and from fuel rod to fuel rod. An implicit solution algorithm is used for both the momentum and energy equations to ease time-step limitations and stability requirements.

HYDRA-II has been designed to provide a user-oriented input interface, which eliminates the need for internal code changes. Any application for which the code is an appropriate choice can be completely described through the construction of an input file. The user may optionally request a formatted echo of the input file to confirm that the intended parameters are actually those used by the code. A selectable commentary monitoring the progress of the code toward a steady-state solution is available, as well as a summary of energy balances. Finally, a tape may be written at the conclusion of a run if the user wishes to restart the solution from its most recent point.

3.0 GOVERNING EQUATIONS

The basic equations that govern the conservation of momentum, mass, and energy are presented in this chapter. The time-dependent conservation equations of momentum and mass for a single-phase fluid are used as the basis for calculating flow fields. The time-dependent conservation equation of energy with convection and heat sources is the basis for calculating temperature fields. These conservation equations are as follows:

Momentum

$$\frac{\partial}{\partial t} (\vec{m}) = \nabla \cdot (\mu \nabla \vec{v}) - \nabla \cdot (\vec{v} \vec{m}) + \rho \vec{g} - \nabla P - D \vec{m} \quad (3.1)$$

where t = time

$\vec{m}$ = mass flux

ρ = density

$\vec{g}$ = gravitational vector

P = pressure

D = Darcy and orifice drag

μ = viscosity

$\vec{v}$ = velocity.

Mass

$$\frac{\partial}{\partial t} (\rho) = -\nabla \cdot (\vec{m}) \quad (3.2)$$

Energy

$$\frac{\partial}{\partial t} (\rho C_p T) = \nabla \cdot (\lambda \nabla T) - \nabla \cdot (C_p \vec{m} T) + q \quad (3.3)$$

where C_p = specific heat

T = temperature

λ = thermal conductivity.

The source term, q , in Equation (3.3) represents heat generation and thermal radiation transport. The latter is given by an expression of the form

$$q_{\text{rad } i \rightarrow j} = H_{ij} (T_i^4 - T_j^4) \quad (3.4)$$

where H_{ij} is an exchange factor based on geometry and emittances. A companion volume, Volume II - User's Manual, describes in detail the exchange factor use within the code. A thermodynamic state relationship of the form

$$\rho = f(p, T) \quad (3.5)$$

is required, as are other relationships needed to define temperature-dependent material properties.

4.0 COMPUTATIONAL MESH

A computational mesh may be defined for both Cartesian and cylindrical coordinate systems. Conventions adopted for the two computational meshes are illustrated in Figures 4.1 and 4.2.

The common procedure is to locate cell boundaries to match physical features of the application, such as where material properties may change discontinuously. Grid points are considered to be located at the geometrical center of each computational cell. Figure 4.3 shows a plane of cells. All field variables and material properties except mass fluxes and cell boundary resistances are defined at cell centers.

Mass fluxes are defined at cell boundaries and have control volumes as illustrated in Figure 4.4.

FIGURE 4.1. Cartesian Mesh

FIGURE 4.2. Cylindrical Mesh

FIGURE 4.3. Computational Cell Construction

FIGURE 4.4. Momentum Control Volumes

The subscripting convention adopted is to denote all quantities related to the cell i, j, k , by no subscript. Furthermore, all subscripting is suppressed, except for those indices that differ from i, j, k . For example:

- $T_{i,j,k}$ denoted by T (temperature centered in cell i, j, k)
- $P_{i+1,j,k}$ denoted by P_{i+1} (pressure centered in cell $i+1, j, k$)
- $\mu_{i+1,j,k+1}$ denoted by $\mu_{i+1,k+1}$ (viscosity centered in cell $i+1, j, k+1$)
- $mx_{i,j,k}$ denoted by mx (mass flux in the x -direction at boundary between cell i, j, k and $i+1, j, k$)
- $my_{i-1,j,k}$ denoted by my_{i-1} (mass flux in the y -direction at boundary between cells $i-1, j, k$ and $i-1, j+1, k$).

This convention provides the same information as other conventions that use three subscripts and fractional subscripts. This compact notation should cause no confusion, so long as the defined position of each variable is kept in mind.

FIGURE 4.4. Momentum Control Volumes

The subscripting convention adopted is to denote all quantities related to the cell i, j, k , by no subscript. Furthermore, all subscripting is suppressed, except for those indices that differ from i, j, k . For example:

- $T_{i,j,k}$ denoted by T (temperature centered in cell i, j, k)
- $p_{i+1,j,k}$ denoted by p_{i+1} (pressure centered in cell $i+1, j, k$)
- $\mu_{i+1/2,j+1/2,k+1/2}$ denoted by $\mu_{i+1/2,j+1/2,k+1/2}$ (viscosity centered in cell $i+1/2, j+1/2, k+1/2$)
- $m_{x,i,j,k}$ denoted by m_x (mass flux in the x -direction at boundary between cells i, j, k and $i+1, j, k$)
- $m_{y,i,j,k}$ denoted by $m_{y,i}$ (mass flux in the y -direction at boundary between cells i, j, k and $i, j-1, k$)

This convention provides the same information as other conventions that use three subscripts and fractional subscripts. This compact notation should cause no confusion, so long as the defined position of each variable is kept in mind.

5.0 DISCRETE FORMS OF THE ENERGY EQUATION

This chapter presents discrete forms of the energy equation given in Chapter 3.0. This chapter also illustrates the method used to obtain the discrete or algebraic equations.

A control-volume formulation is used to derive the algebraic equations from the basic differential equation. One attractive feature of the control-volume formulation is the ease with which physical features, such as discontinuous material properties, may be expressed mathematically. Another important attribute of the control-volume approach is that conservation equations are expressed in an integral conservation form over any group of computational cells. The control-volume formulation used in HYDRA-II is well known but will be described briefly to illustrate the method. A very readable description of the method may be found in Patankar (1980).

The general methodology is as follows. The steady-state form of the basic differential equation is solved in each of the three orthogonal coordinate directions as if there were three independent one-dimensional problems. The heat flow in the coordinate-axis direction is given in terms of the basic parameters of the differential equation, finite lengths of the volume, and temperature at two volume end points. The heat flows thus determined are then applied at the six faces of a three-dimensional finite control volume. The resulting expression represents a statement of conservation of energy for the control volume.

5.1 CARTESIAN COORDINATES

The conservation of energy for steady-state one-dimensional heat transfer may be expressed as

$$\frac{d}{dx} \left(\lambda \frac{dT}{dx} \right) - \frac{d}{dx} (C_p \dot{m} T) = q \quad (5.1)$$

where C_p is the specific heat of fluid and $\dot{m}$ is mass flux in the x-direction.

Equation (5.1) is treated as a linear second-order ordinary differential equation with constant coefficients whose solution can easily be found by standard methods.

The total flow of heat, $Q(x)$, along a body of cross-sectional area $\Delta y \Delta z$ and length X found from the solution of Equation (5.1) is

$$\begin{aligned} \frac{XQ(x)}{\lambda \Delta y \Delta z} = & \left(Pe + \frac{Pe}{e^{Pe}-1} \right) T(0) = \left(\frac{Pe}{e^{Pe}-1} \right) T(X) \\ & + \left[\frac{x}{X} - \frac{1}{Pe} \left(1 - \frac{Pe}{e^{Pe}-1} \right) \right] \frac{x^2 q}{\lambda} \end{aligned} \quad (5.2)$$

$$\text{where } Pe = \frac{c_p m x X}{\lambda} \quad (\text{Peclet number}) \quad (5.3)$$

and $T(0)$ and $T(X)$ are temperatures at the two ends of the body.

An expression for the total flow of heat crossing a computational cell boundary will shortly be needed. In anticipation of this need, it is helpful to evaluate Equation (5.2) at each end of the body.

$$\frac{XQ(0)}{\lambda \Delta y \Delta z} = g(Pe) T(0) - f(Pe) T(X) - f_q(Pe) \frac{x^2 q}{\lambda} \quad (5.4a)$$

$$\frac{XQ(X)}{\lambda \Delta y \Delta z} = g(Pe) T(0) - f(Pe) T(X) + g_q(Pe) \frac{x^2 q}{\lambda} \quad (5.4b)$$

$$\text{where } f(Pe) = \frac{Pe}{e^{Pe}-1} \quad (5.4c)$$

$$g(Pe) = Pe + f(Pe) \quad (5.4d)$$

$$f_q(Pe) = \frac{1}{Pe} [1 - f(Pe)] \quad (5.4e)$$

$$g_q(Pe) = 1 - f_q(Pe) \quad (5.4f)$$

The body may be divided into control volumes extending along its length. Figure 5.1 shows two of the control volumes denoted by cells i and $i+1$.

FIGURE 5.1. Two Typical Energy Control Volumes

An expression for the energy crossing the interface between cell i and $i+1$ may now be formulated using the cell centered temperatures. Peclet numbers are required for three regions: the right half of cell i , the interface between cells i and $i+1$, and the left half of cell $i+1$.

$$Pe^- = C_p mx \left(\frac{\Delta x}{2\lambda} \right) \quad (5.5a)$$

$$Pe^i = C_p mx \left(\frac{\delta}{\lambda} \right) = C_p mx \frac{1}{h} \quad (5.5b)$$

$$Pe^+ = C_p mx \left(\frac{\Delta x}{2\lambda} \right)_{i+1} \quad (5.5c)$$

In Equation (5.5b), h represents an interfacial conductance. Equations (5.4a) through (5.4f) are applied to each region.

$$g^-T - f^-T_b^- + gq^- \left(\frac{\Delta x^2 a}{4\lambda} \right) = \left(\frac{\Delta x}{2\lambda} \right) \frac{Q}{\Delta y \Delta z} \quad (5.6a)$$

$$g^i T_b^- - f^i T_b^+ = \frac{1}{h} \frac{Q}{\Delta y \Delta z} \quad (5.6b)$$

$$g^+ T_b^+ - f^+ T_{i+1} - fq^+ \left(\frac{\Delta x^2 q}{4\lambda} \right)_{i+1} = \left(\frac{\Delta x}{2\lambda} \right)_{i+1} \frac{Q}{\Delta y \Delta z} \quad (5.6c)$$

Temperatures at each side of the cell boundary are denoted by T_b^- and T_b^+ . The desired expression for the energy crossing the cell boundary is determined from Equations (5.6a) through (5.6c).

$$Q_{i \rightarrow i+1} = \frac{\Delta y \Delta z}{g^i g^+ \left(\frac{\Delta x}{2\lambda} \right) + f^- g^+ \frac{1}{h} + f^- f^i \left(\frac{\Delta x}{2\lambda} \right)_{i+1}} \left\{ g^- g^i g^+ T - f^- f^i f^+ T_{i+1} + \frac{1}{4} \left[g^i g^+ gq^- \left(\frac{\Delta x^2 q}{\lambda} \right) - f^- f^i fq^+ \left(\frac{\Delta x^2 q}{\lambda} \right)_{i+1} \right] \right\} \quad (5.7)$$

Equation (5.7) may be expressed in compact notation for easier manipulation as

$$Q_{i \rightarrow i+1} = CI T - AI T_{i+1} + SI \quad (5.8)$$

An expression for the energy flowing from cell $i-1$ to cell i is given by simply decrementing the spatial index i by one. Expressions for energy flow in the other two coordinate directions are obtained by an appropriate permutation of x , y , and z , and replacement of the spatial index by j or k .

The total energy, ΣQ , flowing into the control volume may now be given using the compact notation of Equation (5.8).

$$\Sigma Q = Q_{i+1 \rightarrow i} + Q_{i-1 \rightarrow i} + \dots + Q_{k-1 \rightarrow k} \quad (5.9a)$$

$$\begin{aligned} &= AI_{i+1} T_{i+1} - (CI + AI_{i-1}) T + CI_{i-1} T_{i-1} + SI_{i-1} - SI \\ &= AJ_{j+1} T_{j+1} - (CJ + AJ_{j-1}) T + CJ_{j-1} T_{j-1} + SJ_{j-1} - SJ \\ &= AK_{k+1} T_{k+1} - (CK + AK_{k-1}) T + CK_{k-1} T_{k-1} + SK_{k-1} - SK \end{aligned} \quad (5.9b)$$

The final discrete representation of the differential equation for the conservation of energy in Cartesian coordinates is

$$\rho C_p \Delta x \Delta y \Delta z \frac{\delta T}{\delta t} = \Sigma Q \quad (5.10)$$

Before moving on to the discrete form of the energy equation in cylindrical coordinates, it is worthwhile to return to a principal approximation: the algebraic equations were derived assuming one-dimensional energy (and mass) flow along a coordinate axis. This assumption is rarely satisfied in three-dimensional problems and is a source of numerical diffusion. However, the benefits of physical interpretation, integral conservation, and numerical stability to the solution of inhomogeneous elliptic problems are arguments in favor of this control-volume method.

The algebraic equations are inherently approximate, and, because of this, it may be expedient to simplify them in the interest of computational efficiency. The convection term in the energy equation led to the introduction of the Peclet number--in fact an exponential function of the Peclet number. The computational expense of evaluating the exponential function is not ordinarily justified. A close approximation to, and a computationally simpler form of, Equations (5.4c) and (5.4e) is used:

$$f(Pe) = \frac{1}{1 + \frac{1}{2} |Pe|} + DIM(0, Pe) \quad (5.11a)$$

$$fq(Pe) = \frac{1}{2} \{SIGN(1,Pe) [MIN(f,g) - 1] + 1\} \quad (5.11b)$$

where DIM, SIGN, and MIN are FORTRAN intrinsic functions.

5.2 CYLINDRICAL COORDINATES

A cylindrical coordinate system is usually employed when an exterior cask body is to be modeled. Cask bodies normally have energy transport only by conduction and have no internal sources of energy. The conservation equation for energy used for cylindrical coordinates therefore has the form

$$\frac{\partial}{\partial t} (\rho C_p T) = \nabla \cdot (\lambda \nabla T) \quad (5.12)$$

The procedure used to derive the discrete analogue of Equation (5.12) is exactly the same as was used in the previous section. A steady-state one-dimensional solution of the right-hand side of Equation (5.12) is determined for each coordinate direction. The total heat flow in each direction is

$$Q(r) = \lambda \Delta \theta \Delta z \frac{T(r_0) - T(r)}{\ln \frac{r}{r_0}} \text{ (radial)} \quad (5.13a)$$

$$Q(\theta) = \lambda \Delta r \Delta z \frac{T(\theta_0) - T(\theta)}{r (\theta - \theta_0)} \text{ (circumferential)} \quad (5.13b)$$

$$Q(z) = \lambda \Delta r r \Delta \theta \frac{T(z_0) - T(z)}{(z - z_0)} \text{ (axial)} \quad (5.13c)$$

where r_0 , θ_0 , and z_0 represent reference positions.

Next, Equations (5.13) are evaluated at the control volume boundary between the reference volume and its nearest neighbor in each direction:

$$Q_{i \rightarrow i+1} = \Delta \theta \Delta z \frac{T - T_{i+1}}{\frac{1}{\lambda} \ln \frac{r_b}{r} + \frac{1}{r_b} \frac{1}{h} + \frac{1}{\lambda_{i+1}} \ln \frac{r_{i+1}}{r_b}} \quad (5.14a)$$

$$= AI (T - T_{i+1}) \quad (5.14b)$$

$$Q_{j \rightarrow j+1} = 2 \frac{\Delta r \Delta z}{r} \frac{T - T_{j+1}}{\left(\frac{\Delta \theta}{\lambda}\right) + \frac{2}{r} \frac{1}{h} + \left(\frac{\Delta \theta}{\lambda}\right)_{j+1}} \quad (5.14c)$$

$$= AJ (T - T_{j+1}) \quad (5.14d)$$

$$Q_{k \rightarrow k+1} = 2r \Delta \theta \Delta r \frac{T - T_{k+1}}{\left(\frac{\Delta z}{\lambda}\right) + 2 \frac{1}{h} + \left(\frac{\Delta z}{\lambda}\right)_{k+1}} \quad (5.14e)$$

$$= Ak (T - T_{k+1}) \quad (5.14f)$$

where r_b is the radius of the boundary between cells i and $i+1$.

Finally, the heat flows in the form shown in Equations (5.14) are summed on all six faces of the control volume to give the discrete form of the conservation equation:

$$\rho C_p \Delta x \Delta y \Delta z \frac{\delta T}{\delta t} = \sum Q = Q_{i+1 \rightarrow i} + Q_{i-1 \rightarrow i} + \dots + Q_{k-1 \rightarrow k} \quad (5.15a)$$

$$\begin{aligned} &= AI (T_{i+1} - T) + AI_{i-1} (T_{i-1} - T) \\ &+ AJ (T_{j+1} - T) + AJ_{j-1} (T_{j-1} - T) \\ &+ AK (T_{k+1} - T) + AK_{k-1} (T_{k-1} - T) \end{aligned} \quad (5.15b)$$

6.0 DISCRETE FORM OF THE LINEAR MOMENTUM EQUATION

This chapter presents the discrete form of the momentum equation given in Chapter 3.0 specialized to Cartesian coordinates.

A control-volume formulation is used to derive the algebraic equations from the basic differential equation. The attractive features of this approach for the linear momentum equation are the same as noted previously for the energy equation, namely: the ease of expressing physical features, such as discontinuous material properties, and the integral conservation form of the resulting equations.

The general methodology used to discretize the linear momentum equation is also the same as that used for the energy equation. Each of the three linear momentum equations is treated identically. The steady-state form of the differential equation is solved in each of the three orthogonal directions as though there were three independent one-dimensional problems. The force in a coordinate axis direction is given in terms of the basic parameters of the differential equation, finite lengths of the volume, and mass fluxes at volume end points. The forces thus determined are then applied at the six faces of a three-dimensional finite control volume. The resulting expression represents a statement of conservation of momentum for the control volume.

Recall that the steady-state equation for conservation of energy may be expressed as

$$\nabla \cdot (\lambda \nabla T) - \nabla \cdot (C_p \dot{m} T) = q \quad (6.1)$$

and the steady-state equation for conservation of linear momentum in the x-direction may be expressed as

$$\nabla \cdot (\mu \nabla u) - \nabla \cdot (\dot{m} u) = \frac{\partial p}{\partial x} - \rho g_x + D_X m_x \quad (6.2)$$

where u represents the velocity in the x -direction. The momentum equations in the y -direction and z -direction are similar in form to Equation (6.2).

The similarity in the form of Equation (6.1) and Equation (6.2) suggests an analogy between temperature and velocity. Solution of the energy equation led to an important dimensionless parameter, the Peclet number,

$$Pe = \frac{C_p m X}{\lambda} \text{ (Peclet number)} \quad (6.3)$$

which represents the ratio of convection to diffusion of energy. An analogous dimensionless parameter, the Reynolds number, appears in the solution of the momentum equation.

$$Re = \frac{m X}{\mu} \text{ (Reynolds number)} \quad (6.4)$$

The Reynolds number also represents the ratio of convection to diffusion, but for momentum transfer rather than energy transfer.

Therefore, this analogy makes it formally possible to carry over the results from the discrete form of the energy equation directly to the discrete form of the momentum equation. The Peclet number is replaced by the Reynolds number, the right-hand side of Equation (6.2) replaces the source term in Equation (6.1), and allowance is made for the staggered grid between the energy and momentum control volumes.

The discrete form of the momentum equation may appear somewhat more complex; certainly, the expressions are longer than they are in the discrete form of the energy equation. The additional length of the expressions is due primarily to the effect of the staggered grid. The finite control volume for momentum spans two cell-centered computational cells. This requires the collection of forces on both cell-centered cells. The details are straightforward and are implemented in a fashion virtually identical to the previously described formulation of the energy equations.

The final discrete representation of the differential equation for the conservation of linear momentum in the x-direction is

$$\begin{aligned}
 CX \frac{\delta mx}{\delta t} = & AI \, mx_{i+1} - BI \, mx + CI \, mx_{i-1} \\
 & + AJ \, mx_{j+1} - BJ \, mx + CJ \, mx_{j-1} \\
 & + AK \, mx_{k+1} - BK \, mx + CK \, mx_{k-1} \\
 & - DX \, mx + GRAVX + P - P_{i+1}
 \end{aligned} \tag{6.5}$$

According to convention, the subscripting is suppressed except for those indices that differ from i, j, k.

The coefficient CX has the form

$$CX = \frac{1}{2} \left[\left(\frac{\Delta x}{AX} \right) + \left(\frac{\Delta x}{AX} \right)_{i+1} \right] \tag{6.6}$$

where AX represents the fraction of the cross-sectional area open to flow in the x-direction. AX is a cell-centered quantity.

The coefficients AI, BI, and CI have the following form:

$$AI = f_{i+1} \left(\frac{\mu}{\rho \Delta x} \right)_{i+1} \tag{6.7a}$$

$$CI = g \left(\frac{\mu}{\rho \Delta x} \right) \tag{6.7b}$$

$$BI = g_{i+1} \left(\frac{\mu}{\rho \Delta x} \right)_{i+1} + f \left(\frac{\mu}{\rho \Delta x} \right) \tag{6.7c}$$

The function f has the same definition as for the energy equation except that the Reynolds number is used in place of the Peclet number:

$$f = f(Re) = \frac{1}{1 + \frac{1}{2} |Re|} + DIM(0, Re) \quad (6.8a)$$

and, similarly for the function g,

$$g = g(Re) = Re + f(Re) \quad (6.8b)$$

The appropriate definition of the Reynolds number for use in AI, BI, and CI is

$$Re = \frac{1}{2} (mx_{i-1} + mx) \left(\frac{\Delta x}{\mu} \right) \quad (6.9)$$

The coefficients AJ, BJ, CJ, AK, BK, and CK prescribe the exchange of momentum between cell i, j, k and surrounding cells with differing j or k (e.g., cell i, j, k+1). The coefficients also account for the staggered grid where, for example, the control volume for mx spans half of computational cell i and half of computational cell i+1. Therefore, in accumulating the momentum exchange, the contributions from cell i and cell i+1 are added.

The coefficients AK, BK, and CK have the following form:

$$AK = AKM_{k+1 \leftarrow k} + AKM_{i+1, k+1 \leftarrow k} \quad (6.10a)$$

$$CK = CKM_{k \leftarrow k-1} + CKM_{i+1, k \leftarrow k-1} \quad (6.10b)$$

$$BK = CKM_{k+1 \leftarrow k} + AKM_{k \leftarrow k-1} + CKM_{i+1, k+1 \leftarrow k} + AKM_{i+1, k \leftarrow k-1} \quad (6.10c)$$

The quantities AKM and CKM represent momentum exchange coefficients that are defined by Equations (6.11). The subscripting convention has the following meaning:

- $k+1 \text{ --- } k$ denotes exchange between cell $i, j, k+1$ and cell i, j, k
- $i+1, k \text{ --- } k-1$ denotes exchange between cell $i+1, j, k$ and cell $i+1, j, k-1$.

The definition of AKM and CKM is

$$AKM_{\ell \text{ --- } m} = \frac{\Delta x}{\Delta z} \frac{f_m f_\ell \alpha_{\ell m}}{f_m \alpha_{\ell m} \left(\frac{\Delta z}{\mu}\right)_\ell + g_\ell \gamma_{\ell m} \left(\frac{\Delta z}{\mu}\right)_m} \frac{1}{\rho_\ell} \quad (6.11a)$$

$$CKM_{\ell \text{ --- } m} = \frac{\Delta x}{\Delta z} \frac{g_m g_\ell \gamma_{\ell m}}{f_m \alpha_{\ell m} \left(\frac{\Delta z}{\mu}\right)_\ell + g_\ell \gamma_{\ell m} \left(\frac{\Delta z}{\mu}\right)_m} \frac{1}{\rho_m} \quad (6.11b)$$

where the subscript $\ell \text{ --- } m$ may have the value $k+1 \text{ --- } k$ or $k \text{ --- } k-1$ according to what is indicated in Equation (6.10). Note that the subscript i has been suppressed but is assumed to be either i or $i+1$ as required.

The quantities f and g appearing in Equation (6.11) have the same functional dependence on the Reynolds number as in Equation (6.8). The appropriate definition of the Reynolds number for use in AK, BK, and CK is

$$Re_m = m z_m \left(\frac{\Delta z}{\mu}\right)_m \quad (6.12a)$$

$$Re_\ell = m z_m \left(\frac{\Delta z}{\mu}\right)_\ell \quad (6.12b)$$

The quantities α and γ appearing in Equation (6.11) are defined as

$$\alpha_{\ell m} = \begin{cases} AZI_m, & \ell \neq k \\ 1, & \ell = k \end{cases} \quad (6.13a)$$

$$\gamma_{lm} = \begin{cases} 1, & l \neq k \\ AZI_{lm}, & l = k \end{cases} \quad (6.13b)$$

AZI represents the fractional open area for flow in the z-direction at the interface between cells m and m+1. For example, AZI_{lm} is the fractional open area between cell i, j, m and cell i, j, m+1.

The coefficients AJ, BJ, and CJ are obtained from AK, BK, CK by simply substituting the letter J for K, Y for Z, and the subscript j for k in Equations (6.10) through (6.13).

The coefficient DX in Equation (6.5) represents fluid drag such as would be present in porous media with permeability, k. Also included in the coefficient DX is a velocity-dependent term such as would arise from flow through an orifice or partial blockage with a fractional open area of AXI. The expression for DX is

$$DX = \frac{1}{2} \left[\left(\frac{\mu \Delta x}{\rho k} \right) + \left(\frac{\mu \Delta x}{\rho k} \right)_{i+1} \right] + \frac{1 - AXI^2}{AXI^2} \frac{|m_x|}{2 \langle \rho \rangle} \quad (6.14a)$$

where the average density, $\langle \rho \rangle$, is given by

$$\langle \rho \rangle = \frac{(\Delta x \rho) + (\Delta x \rho)_{i+1}}{\Delta x + \Delta x_{i+1}} \quad (6.14b)$$

The term GRAVX in Equation (6.5) represents the effect of gravity on momentum transport in the x-direction. The expression for GRAVX is

$$GRAVX = \frac{1}{2} \left[(\rho \Delta x) + (\rho \Delta x)_{i+1} \right] g_x \quad (6.15)$$

where g_x is the x-component of the gravitational vector.

7.0 DISCRETE FORM OF THE CONTINUITY EQUATION

The discrete form of the continuity equation follows directly from the basic concept of conservation of mass: the net outflow of mass across the surface of a volume will equal the rate of decrease of mass within the volume (in the absence of a source of mass). For computational purposes, the reference volume selected is just a computational cell. The mass fluxes are defined at the six faces of the computational cell, and the density is cell-centered.

The conservation of mass is represented in discrete form as

$$\Delta x \Delta y \Delta z \phi \frac{\delta \rho}{\delta t} = (m x_{i-1} - m x) \Delta y \Delta z + (m y_{j-1} - m y) \Delta x \Delta z + (m z_{k-1} - m z) \Delta x \Delta y \quad (7.1)$$

where the porosity of the cell is denoted by ϕ . The porosity is a cell-centered quantity.

8.0 SOLUTION PROCEDURE FOR THE ENERGY EQUATION

The set of algebraic equations approximating the solution of the energy equation within a domain has the form

$$\begin{aligned}\rho C_p V \frac{\delta T}{\delta t} = & AI T_{i+1} - BI T + CI T_{i-1} \\ & + AJ T_{j+1} - BJ T + CJ T_{j-1} \\ & - AK T_{k+1} - BK T + CK T_{k-1} + q\end{aligned}\quad (8.1)$$

The solution procedure can be illustrated rather simply by defining the finite difference operators

$$LI T = AI T_{i+1} - BI T + CI T_{i-1} \quad (8.2a)$$

$$LJ T = AJ T_{j+1} - BJ T + CJ T_{j-1} \quad (8.2b)$$

$$LK T = AK T_{k+1} - BK T + CK T_{k-1} \quad (8.2c)$$

and

$$L = LI + LJ + LK \quad (8.2d)$$

Introducing Equation (8.2) into Equation (8.1) gives

$$\rho C_p V \frac{\delta T}{\delta t} = (LI + LJ + LK) T + q \quad (8.3a)$$

$$= L T + q \quad (8.3b)$$

The meaning of δT on the left-hand side of Equation (8.3) is just the change in temperature from the preexisting temperature, that is, $T - T^0$ where the superscript indicates old-time temperature. The temperature appearing explicitly on the right-hand side of Equation (8.3), however, need not be the new-time temperature. Some flexibility may be introduced into Equation (8.3) by adding a temporal weighing factor, θ . Equation (8.3b) becomes

$$\rho C_p V \frac{\delta T}{\delta t} = \theta L T + (1-\theta) L T^0 + q \quad (8.4)$$

For θ equal to zero the heat flowing into a computational cell is based entirely on old-time temperatures. The new-time temperatures are easy to compute, but the time step δt may need to be restricted to avoid numerical instability. For θ in the range $1/2 < \theta < 1$, it is possible to avoid numerical instability (depending on the functional dependence of L and q on temperature) but at the expense of more computational effort. The additional computational effort is, fortunately, not great and is considered a relatively small price to pay for unconditional stability. HYDRA-II is designed to restrict θ to the range $1/2 < \theta < 1$.

The right-hand side of Equation (8.4) may be written as

$$\rho C_p V \frac{\delta T}{\delta t} = \theta L (T - T^0) + L T^0 + q \quad (8.5)$$

and, because $T - T^0$ equals δT , the final form of the energy equation is

$$(CAP - L) \delta T = \frac{1}{\theta} (L T^0 + q) \quad (8.6)$$

where

$$CAP = \frac{\rho C_p V}{\theta \delta t} \quad (8.7)$$

The sparse matrix, CAP-L, may be approximately factored into the product of three tridiagonal matrices, which are easy to solve. The details of this approximate factorization and solution technique may be found in Douglas and Gunn (1964). The factorization and solution proceeds as follows. Equation (8.6) is factored (approximately) as

$$(CAP-LI) \frac{1}{CAP} (CAP-LJ) \frac{1}{CAP} (CAP-LK) \delta T = \frac{1}{\theta} (L T^{\circ} + q) \quad (8.8)$$

by recalling that $L = LI + LJ + LK$. Three tridiagonal matrix equations are solved in succession:

$$(CAP-LI) \delta T^* = \frac{1}{\theta} (L T^{\circ} + q) \quad (8.9a)$$

$$(CAP-LJ) \delta T^{**} = CAP \delta T^* \quad (8.9b)$$

$$(CAP-LK) \delta T = CAP \delta T^{**} \quad (8.9c)$$

and, finally, the new-time temperature is obtained from

$$T = T^{\circ} + \delta T \quad (8.10)$$

In addition to the advantages of simplicity and stability, this procedure approaches the correct steady-state answer in spite of the approximate factorization employed.

9.0 SOLUTION PROCEDURE FOR THE MOMENTUM AND CONTINUITY EQUATIONS

The set of algebraic equations approximating the solution of the x-direction linear momentum equation has the form

$$\begin{aligned}
 CX \frac{\delta m_x}{\delta t} = & AI \, m_{x,i+1} - BI \, m_x + CI \, m_{x,i-1} \\
 & + AJ \, m_{x,j+1} - BJ \, m_x + CJ \, m_{x,j-1} \\
 & + AK \, m_{x,k+1} - BK \, m_x + CK \, m_{x,k-1} \\
 & - DX \, m_x + GRAVX + P - P_{i+1}
 \end{aligned} \tag{9.1}$$

The form of the equations for m_y and m_z is similar to that for m_x . The solution procedure can be illustrated as was done previously with the energy equation. Equation (9.1) becomes, after introducing the finite difference operator L defined by Equation (8.2) and the temporal weighing factor θ ,

$$\begin{aligned}
 (CAPX-L) \, \delta m_x = & \frac{1}{\theta} (L-DX) \, m_x^{\circ} + GRAVX + \frac{1-\theta}{\theta} GRAVX^{\circ} \\
 & + \left[(P-P^{\circ}) - (P_{i+1}-P_{i+1}^{\circ}) \right] + \frac{1}{\theta} (P^{\circ}-P_{i+1}^{\circ})
 \end{aligned} \tag{9.2}$$

The temporal weighing factor θ is again restricted to the range $1/2 < \theta < 1$, the superscript $^{\circ}$ signifies old-time values, and CAPX has the definition

$$CAPX = \frac{CX}{\theta \delta t} + DX \tag{9.3}$$

The solution procedure selected involves determining three mass fluxes using their respective linear momentum equations, followed by determination of pressure using the continuity equation. The solution for mass fluxes and pressure is not done simultaneously, and this presents a problem in Equation (9.2): both mass flux and pressure appear. The simplest remedy to this situation is to take sufficiently small time-steps such that the change in pressure over a

which provides a simple relationship between mass flux and pressure if the term $L (m_x - \tilde{m}_x)$ is neglected. Such an approximation is acceptable for sufficiently small time-steps and is consistent with the approximation made previously by using Equation (9.4) instead of Equation (9.2). Therefore, the equation relating new-time mass flux to new-time pressure is

$$m_x = \tilde{m}_x + \frac{1}{CAPX} (\delta P - \delta P_{i+1}) \quad (9.7)$$

The discrete form of the continuity equation was derived in Chapter 7.0 and is repeated here as Equation (9.8):

$$\begin{aligned} \Delta x \Delta y \Delta z \phi \frac{\delta \rho}{\delta t} &= (m_{x_{i-1}} - m_x) \Delta y \Delta z + (m_{y_{j-1}} - m_y) \Delta x \Delta z \\ &\quad + (m_{z_{k-1}} - m_z) \Delta x \Delta y \\ &= \text{DIV}(m) \end{aligned} \quad (9.8)$$

The definition of m_x (Equation 9.7) and analogous definitions for m_y and m_z are next introduced into Equation (9.8). This is easily done with the aid of the following definitions:

$$AI = \frac{\Delta y \Delta z}{CAPX} \quad (9.9a)$$

$$AJ = \frac{\Delta x \Delta z}{CAPY} \quad (9.9b)$$

$$AK = \frac{\Delta x \Delta y}{CAPZ} \quad (9.9c)$$

The result is Equation (9.10),

$$\begin{aligned}
\Delta x \Delta y \Delta z \phi \frac{\delta \rho}{\delta t} = & AI \delta P_{i+1} - (AI + AI_{i-1}) \delta P + AI_{i-1} \delta P_{i-1} \\
& + AJ \delta P_{j+1} - (AJ + AJ_{j-1}) \delta P + AJ_{j-1} \delta P_{j-1} \\
& + AK \delta P_{k+1} - (AK + AK_{k-1}) \delta P + AK_{k-1} \delta P_{k-1} \\
& + \text{DIV}(\tilde{m})
\end{aligned} \tag{9.10a}$$

$$= L \delta P + \text{DIV}(\tilde{m}) \tag{9.10b}$$

where L is the finite difference operator apparent from Equation (9.10a).

The density, ρ , appearing in Equation (9.10) may be expressed in terms of pressure

$$\frac{\delta \rho}{\delta t} = \frac{1}{\delta t} \left[\rho^0 + \left(\frac{\partial \rho^0}{\partial T} \right)_{\rho} \delta T + \left(\frac{\partial \rho^0}{\partial P} \right)_T \delta P - \rho^0 \right] \tag{9.11}$$

The first two terms on the right-hand side of Equation (9.11),

$$\rho^0 + \left(\frac{\partial \rho^0}{\partial T} \right)_{\rho} \delta T,$$

represent the old-time density, adjusted for the change in temperature, which has been previously determined and used in the momentum equations (i.e., GRAV). This thermally expandible density, ρ_T , therefore equals

$$\rho_T = \rho^0 + \left(\frac{\partial \rho^0}{\partial T} \right)_{\rho} \delta T \tag{9.12}$$

The final form of the discrete continuity equation is, after substituting Equation (9.12) into (9.10b),

$$\left[\Delta x \Delta y \Delta z \phi \frac{1}{\delta t} \left(\frac{\partial \rho^{\circ}}{\partial p} \right)_T - L \right] \delta P = \text{DIV}(\tilde{m}) - \Delta x \Delta y \Delta z \phi \frac{1}{\delta t} (\rho_T - \rho^{\circ}) \quad (9.13)$$

Equation (9.13) is solved using a line successive overrelaxation algorithm. New-time pressures are obtained from

$$p = p^{\circ} + \delta P \quad (9.14)$$

and new-time mass flux is obtained from Equation (9.7). New-time density is obtained from the updated pressure and current temperature using the equation of state for the fluid. This completes the computation for one time-step. A new time-step begins by returning to the energy equation with the updated values of mass fluxes and, if needed, pressure and density.

REFERENCES

- DOE. 1985. Spent Fuel Storage Requirements. DOE/RL-85-2, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
- Douglas, J., and J. Gunn. 1964. "A General Formulation of Alternating Direction Methods." I. Numer. Math. 6:428.
- McCann, R. A. 1980. HYDRA-I: A Three-Dimensional Finite Difference Code for Calculating the Thermohydraulic Performance of a Fuel Assembly Contained Within a Canister. PNL-3367, Pacific Northwest Laboratory, Richland, Washington.
- Patankar, S. V. 1980. Numerical Heat Transfer and Fluid Flow. Hemisphere, Washington, D.C.

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