coefficient of friction.

Conservation of energy.

$$\frac{\partial e}{\partial t} = \frac{1}{m}\left\{\phi m' S[(u - u_w)^2/2 + (e_w - e)] - p\frac{\partial V}{\partial t} + T_w S\,|u| + H'\right\} \quad (A3)$$

The specific internal energy, e, is modified by: the entering mass, whose specific internal energy is e_w and whose velocity is u_w; volume changes; irreversible dissipative work done on a zone by the tunnel surface stresses; and (H' = energy/time) energy sources or sinks.

Equation of state. The functions can be any equation or table for each material present.

Heat transfer. The energy sink H' can be due to turbulent convective heat flux q_c and a radiative heat flux q_r. These heat fluxes transfer energy through the surface area S of the zone that is in contact with the tunnel walls. The heat fluxes are calculated by *Bond, Watson and Welch* [1965], *Schlichting* [1960], and *Rose and Offenhartz* [1959]

$$H' = -S(q_c + q_r) = -S\left(\frac{C_H \gamma p u}{\gamma - 1} + \frac{4\sigma T^4}{3\rho K_R(R/2)}\right) \quad (A4)$$

where p is pressure, u is particle velocity, γ is the ratio of specific heats, C_H is the dimensionless coefficient of turbulent heat transfer (the Stanton number), σ is the Stefan-Boltzmann constant, T is the temperature of the gas, and K_R is the Rosseland mean opacity, which is obtained from a temperature- and density-dependent table.

Ablation mass flux. The mass flux that enters the flow, m', is related to H' by

$$m' = \frac{q_c + q_r}{q^*} = -\frac{H'}{Sq^*} \quad (A5)$$

where

$$q^* = E_v + \eta h \quad (A6)$$

and q^* is the energy required to ablate a unit mass of wall material, E_v is the total specific heat required to vaporize wall material ($E_v \approx 10^{11}$ ergs/g for rock), h is the specific total enthalpy of the gas flow in the tunnel, and η is the turbulent transpiration coefficient ($\eta \approx 0.2$ for rock) [*Rose and Offenhartz,* 1959].

APPENDIX B. TURBULENT DIFFUSION OF ABLATED WALL MASS

A set of hypothetical Eulerian regions are considered axially along the walls of the tunnel. When ablation starts in one of these regions, the time T_s is noted. Then, at any later time T the time interval $T_t = T - T_s$ can be calculated. T_t is the time during which turbulent diffusion has carried gas a distance Y [*Schlichting,* 1960], measured *from* the wall, where

$$Y = R\left\{1 - \left[1 - \frac{T_t u(C_f/2)^{1/2}}{2R}\right]^2\right\} = R[1 - (1 - \beta)]^2 \quad (B1)$$

and R is pipe radius, u is free stream velocity, $C_f/2$ is the dimensionless coefficient of friction, and all quantities are averaged over the Pufl zones within a hypothetical Eulerian wall region.

Until the mass leaving the wall diffuses to the center of the pipe, the calculated ablation mass flux has only a partial effect on the total Pufl zone. It is assumed that this partial effect is proportional to the volume of the Pufl zone that the entering mass occupies at any time. The ratio of the volume occupied by the entering mass to the volume of the inside of the pipe is denoted by ϕ and calculated for each Eulerian region by

$$\phi = 1 - (R - Y)^2/R^2 = 1 - (1 - \beta)^4 \quad (B2)$$

The ablation mass fluxes, calculated for each Lagrangian Pufl zone by equation A5, are multiplied by the appropriate ϕ, depending on the Eulerian region in which the almost-Lagrangian Pufl zone is located.

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