| $F_1, F_2$ | = velocity integrals defined by Eqs. 17 and 18 |
| $f$ | = velocity function, defined by Eq. 6 |
| $K, M, N$ | = constants, defined by Eqs. 1 to 3 and 12 to 14 |
| $r_o$ | = jet exit radius (m) |
| $r_1$ | = radius of potential core (m) |
| $r_2$ | = radius of jet edge (m) |
| $U$ | = velocity (m/s) |
| $U_o$ | = velocity at jet exit (m/s) |
| $x$ | = axial distance (m) |
| $x_o$ | = length of potential core (m) |
| $y_1$ | = radial distance, Figure 1 |

**Greek Letters**

| $\rho$ | = density (kg/m³) |
| $\rho_o$ | = density at nozzle exit (kg/m³) |
| $\rho_a$ | = density of air (kg/m³) |
| $\eta$ | = dimensionless radial distance |
| $\psi$ | = particle concentration (kg particles/kg air) |
| $\psi_o$ | = initial particle concentration (kg particles/kg air) |

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# Measuring Temperature in a Flowing Gas-Solids Suspension with a Thermocouple

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Much research effort during the last two decades has been directed at understanding the heat-transfer characteristics of flowing gas-solids suspensions. This activity has been due to: (1) the usefulness of suspensions as heat-transfer media in situations of high temperature and/or high heat flux (e.g., nuclear reactors); and (2) a growing interest in entrained-flow reactors (e.g., coal pyrolysis).

When a gas-solids suspension flows through a heated tube, heat is transferred from the tube wall to the gas and from the gas to the particles. In addition, the particles gain heat directly from the wall by radiation and possibly by particle-wall collisions. Therefore, it is possible for the temperature of the solids to be either greater than or less than the temperature of the gas, depending on the rate of direct wall-to-particle heat transfer as compared with the rates of wall-to-gas heat transfer and gas-to-particle heat transfer.

In order to accurately analyze the kinetic and transport processes in gas-particle systems, it is necessary to know the temperatures of the gas and particle phases. The particle temperature in coal combustion and pyrolysis, for example, determines the rate of coal devolatilization and heterogeneous reaction as well as the rate of radiation heat transfer from the particles to the reactor wall. The gas temperature governs the rate of gas-phase reactions and wall-to-gas heat transfer. Due to the difficulty of measuring the temperature of the gas and solids independently, most investigators of heat transfer in gas-solids suspensions have assumed that the rate of gas-to-particle heat transfer is infinite, and that the particles and gas are in thermal equilibrium. However, this assumption is not practical for many systems of interest. Calculations by Bransford and Holden (1970), for 56-$\mu$m coal particles suspended in hydrogen gas flowing through a 0.0095-m-diameter tube 0.20 m long at typical reactor conditions (pressure 101.3 kPa, gas velocity 2.3 m/s, and tube wall temperature 1,750 K) show, for example that particle temperature lags gas temperature by approximately 550 K (1,000°R) at the tube outlet. Their conditions correspond to laminar flow (gas Reynolds number equals 120). Particle temperature probably does not lag that of the gas by as great an amount in turbulent flow. However, the need is evident for distinguishing between temperatures of gas and solid phases when analyzing the heat-transfer characteristics of many gas-solids suspensions of interest.

Particle temperature has been determined directly from radiation measurements using two-color pyrometry (Themelis and Gauvin, 1962), and this is probably the preferred method for high-temperature, reacting systems. Boothroyd (1971, p. 91) reports that "stout" thermocouples inserted directly into the flow have been found to register the gas temperature correctly. However, ther-
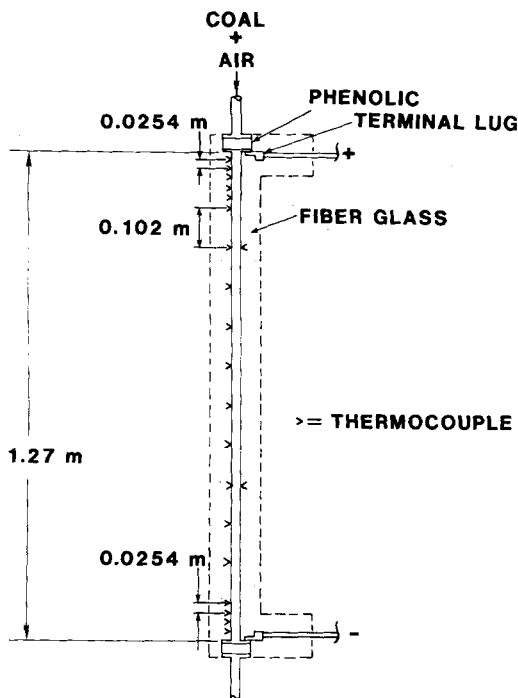
Figure 1. Apparatus used for measuring rate of heat transfer to gas-particle suspensions flowing downward through a vertical heated tube.



Figure 3. Measured temperature profiles (uncorrected for particle impact heating) for upstream thermocouple in 100-$\mu$m suspension.

mocouples often show an abnormally high temperture which is usually attributed to frictional heating by impacting particles. Using the techniques reported in this paper, the particle impact-heating effect was measured for two probe configurations in a flowing suspension of coal particles, one with the thermocouple pointing upstream and another with the thermocouple pointing downstream. The impact heating of the upstream thermocouple was significant and was calibrated, while the heating of the downstream thermocouple was negligible.

The experimental apparatus is completely described elsewhere (Brewster, 1979). Coal particles (100-$\mu$m or 300-$\mu$m) and air were caused to flow cocurrently downward through a 0.01264-m inside diameter by 7.3-m-long vertical stainless-steel tube at various gas velocities ranging from 9.1 to 43 m/s and for particle flow rates of zero to 0.0189 kg/s. Heat was transferred to the gas and particles in a 1.27-m long heat transfer section (Figure 1) that was insulated from the rest of the tube by two phenolic sections and electrically heated by a DC current passing directly through the tube.

The gas temperature at the exit of the heat transfer section was measured by a chromel-alumel (Type K) thermocouple in a stainless-steel sheath inserted into the flow through the wall of the lower phenolic insulator. Two thermocouple configurations were used as shown in Figure 2. The thermocouple junction and wire extended approximately 0.013 m beyond the end of the small-diameter stainless-steel sheath and the wire was bent at a right angle
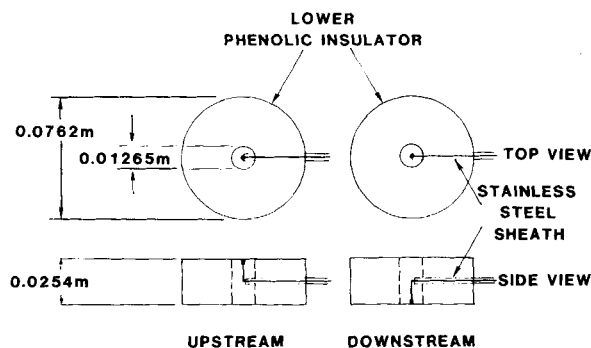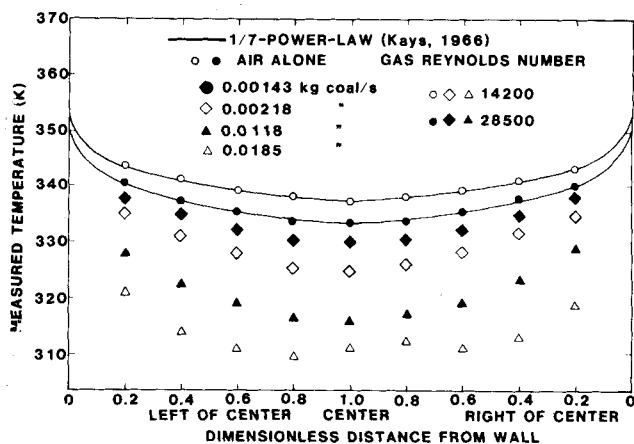
to the axis of the sheath in order to minimize conduction in the wire near the junction. In the first configuration, the sheath diameter was 0.00318 m and the thermocouple faced upstream, into the flow. In the second configuration, the sheath diameter was 0.00159 m and the thermocouple faced upstream. A scale was attached to the outside of the lower flange connection to indicate the radial position of the thermocouple.

Radial gas temperature profiles measured with the upstream thermocouple for turbulent flow of air alone (no coal particles) are symmetrical and agree very well with the 1/7-power law model (e.g., Kays, 1966, p. 162) as shown in Figure 3 for gas Reynolds numbers of 14200 and 28500 (compare open and solid circles with solid curves). Profiles measured in air alone with the downstream thermocouple (compare circles with solid lines in Figures 4 and 5) were somewhat distorted due to radial mixing caused by the sheath, and agreement with the 1/7-power-law model is not quite as good as with the upstream thermocouple. However, the radially averaged temperatures indicated by the upstream and downstream thermocouples were approximately equal at both gas flow rates.

When 100-$\mu$m coal particles were added to the air stream and the electrical power input to the heated tube was adjusted so as to keep the wall temeprature near the exit of the tube constant at 366.4 K, the gas temperature indicated by the upstream thermocouple was lower than for air alone at all radial positions as shown in Figure 3. The reason for the decrease in outlet temperature of the
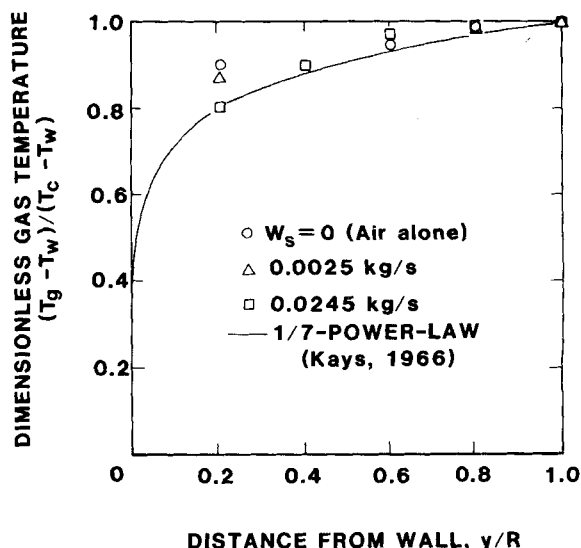


Figure 2. Thermocouple probes used to measure gas temperature in flowing suspensions of gas particles.



Figure 4. Dimensionless temperature profiles measured with downstream thermocouple in 300-$\mu$m suspension (gas Reynolds number $\cong$ 14,200).
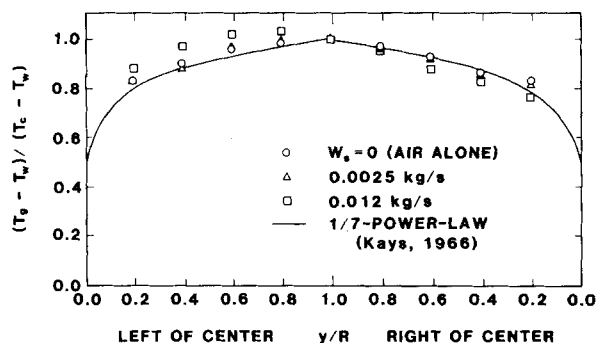
Figure 5. Dimensionless temperature profiles measured with downstream thermocouple in 300-$\mu$m coal suspension (gas Reynolds number $\cong$ 28,400).



Figure 7. Correlation for impact heating of upstream thermocouple in 100-$\mu$m coal suspension.

gas when coal particles are added to the air is that the particles do not significantly increase the heat transfer coefficient from the wall to the gas, but they do have a significant effect on the heat capacity of the suspension, and therefore, for a given amount of heat transfer to the suspension, the fraction used for heating the gas is less. The temperatures indicated by the downstream thermocouple at the same conditions as shown in Figure 3 were as much as 7 K lower than the values shown in Figure 3. The magnitude of the discrepancy between the upflow and downflow thermocouples varied with radial position and with the gas and solids flow rates, and was attributed to frictional heating of the probe by impacting particles.

The frictional heating effect of the particles was investigated quantitatively by making several runs at room temperature. In the absence of particles, the upstream thermocouple indicated the true temperature of the air. However, when the 100-$\mu$m coal particles were added to the air stream, the temperature rose by as much as 7 K depending on the radial position and gas and solids flow rates as shown in Figure 6. This increase matches the discrepancy in the indications of the upstream and downstream thermocouples in heated suspensions. The downstream thermocouple exhibited negligible effects (less than 0.5 K temperature rise) in similar experiments. The stainless-steel sheath and thermocouple wire probably shield the downstream thermocouple from head-on collisions with particles. Data in Figure 6 show that frictional heating of the upstream thermocouple in the 100-$\mu$m suspension was not symmetrical about the tube axis at high solids loading ratios (kg coal/kg air throughout). The reason for this distortion is not known, but may be due to slight curvature in the tube, slight wall disturbance at the lower phenolic insulator, or rebounding particles from the stainless-steel sheath. In any case, cold flow measurements
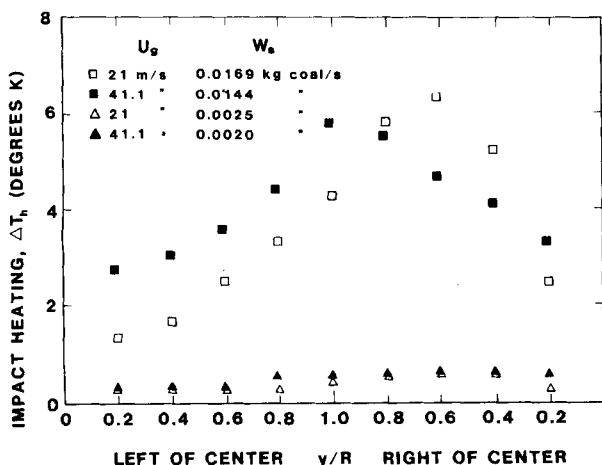
(such as those shown in Figure 7) can be used to correct for the effect of particle frictional heating as follows:

$$T_g = T'_g - \Delta T_h, \qquad (1)$$

where $T_g$ is the true gas temperature, $T'_g$ is the indicated gas temperature, and $\Delta T_h$ is the frictional heating effect (measured for cold flow at the same conditions of gas velocity and particle flowrate.

Frictional heating of the upstream thermocouple at the center of the tube in the 100-$\mu$m suspension was successfully correlated by

$$\Delta T_h = kW_sU_g^{0.6}. \qquad (2)$$

Data are compared with Eq. 2 in Figure 7. Hence, frictional heating is directly proportional to the concentration of particles and increases as the velocity (and kinetic energy) of the particles increases. Sufficient data were not taken for obtaining a correlation that accounts for radial position.

Erosion of the upstream thermocouple was so severe in the 300-$\mu$m suspension that the probe was impractical to use. However, the downstream thermocouple configuration proved satisfactory. Typical exit-gas temperature profiles for the 300-$\mu$m suspension are shown in Figures 4 and 5. No thermocouple radiation shields were used in these experiments since the maximum wall temperature was fairly low (366.4 K).

## ACKNOWLEDGMENTS

Figure 6. Particle impact-heating profiles for upstream thermocouple in 100-$\mu$m suspension flowing through unheated tube.
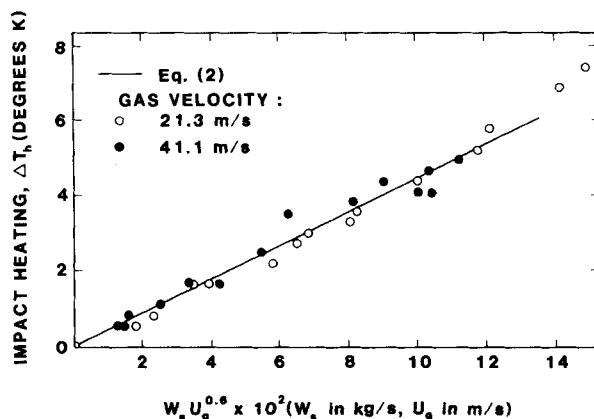
## NOTATION

$k$   = constant in Eq. 2
$R$   = radius of tube
$T_c$   = gas temperature at tube axis
$T_g$   = actual gas temperature
$T'_g$   = gas temperature indicated by thermocouple in flowing gas-solids suspension
$\Delta T_h$ = difference between $T'_g$ and $T_g$ due to heating effect of impacting particles
$T_W$  = wall temperature
$U_g$  = gas velocity (m/s)
$W_s$  = solids flow rate (g coal/s)
$Y$   = distance from wall

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# Thermal Regeneration of Adsorption Beds: Equilibrium Theory for Solute Condensation

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This paper elaborates on a previous article (Friday and LeVan, 1982) in which it was shown that a liquid phase of the adsorbed species can be developed in and passed through an adiabatic adsorption bed during thermal regeneration with a hot purge gas. Two systems were considered: activated carbon, benzene, nitrogen and 4A molecular sieve, water, methane. Material and energy balances were integrated numerically using the method of lines-based equilibrium stage model. While very flexible in that nonconstant initial and feed conditions can be considered without complication, this approach introduces dispersion into the calculated results by the finite difference approximation of axial derivatives.

From a fundamental standpoint it is of interest to establish, for local equilibrium and without dispersion, which transitions are abrupt (shocks) and which are gradual. Then in deep beds with finite mass and heat transfer rates and nonzero dispersion, it is well known that the abrupt transitions become constant patterns and the gradual transitions remain as proportionate patterns. The stage model, without a prohibitively large number of stages, does not give the resolution necessary to identify the true character of all transitions, particularly those of combined form which typically have both gradual and abrupt parts.

In this paper the equilibrium theory for adiabatic adsorption in fixed beds (Amundson et al., 1965; Rhee and Amundson, 1970; Rhee et al., 1970; Pan and Basmadjian, 1970, 1971; Banks, 1972; Basmadjian et al., 1975) is extended to permit treatment of thermal regeneration with solute condensation. This approach is especially well suited to problems with constant initial and boundary conditions. A recent modification of the basic equilibrium theory allows for graphical construction of equilibrium paths and approximate treatment of the influence of transfer resistances (Basmadjian, 1980a). Parallel advances have been made in constructing an equilibrium theory for the throughflow drying and aeration of beds of cereal grain or wool (Sutherland et al., 1971; Norton and Bainbridge, 1972; Basmadjian, 1980b, 1981). In no case, however, have the complicating effects of condensation been considered.

Here, previous work on the equilibrium theory is recast into a form convenient for treating the adsorbed phase in problems involving condensation, using $q$ and $T$ as dependent variables. Then new theory is proposed for the condensed phase. The theory is

applied to the two base cases considered in our previous article. Solutions are obtained with no smearing of concentration and temperature profiles.

## EQUILIBRIUM THEORY

The solution to a system determined by two conservation laws will involve two transitions. Each may be entirely gradual, entirely abrupt, or of combined form. In referring to transitions we follow Rhee et al. (1970) and call the first to leave the bed the one wave and the second the two wave.

The notation used in our previous article is adopted here. When an equation from that paper is referred to its number is preceded by I. The general phase equilibria relation is taken to be $c = c(q, T)$. (Here we recognize that if liquid is present $q$ cannot be determined from a relation of the form $q = q(c, T)$ and, furthermore, $c$ and $T$ are not independent.) A clarification concerning $v^*$ is necessary if liquid should fill part of the interstitial void space. It is then the product of the dimensionless interstitial velocity and the fraction of the interstitial void space that is free of liquid.

### Adsorbed Phase

The material and energy balances given by Eqs. I-8 and I-9 form a reducible quasilinear hyperbolic system. Application of the hodograph transformation to these equations for constant initial and boundary conditions gives for a gradual transition the relation between directional derivatives

$$\frac{\tau}{\zeta} = \rho_b \frac{dq}{d(v^*c)} = \rho_b \frac{dh_s}{d(v^* \rho_f h_f)} \tag{1}$$

Following our earlier treatment, the mole fraction of solute in the vapor phase is taken to be small compared to that for purge gas. Then, the product $v^* \rho_f h_f$ is only a function of temperature and Eq. 1 can be written in terms of the directional derivative $dq/dT$ as:

$$\left[ \frac{\partial(v^*c)}{\partial q} \frac{\partial h_s}{\partial q} \right] \left( \frac{dq}{dT} \right)^2 + \left[ \frac{\partial(v^*c)}{\partial q} \frac{\partial h_s}{\partial T} + \frac{\partial(v^*c)}{\partial T} \frac{\partial h_s}{\partial q} \right.$$
$$\left. - \frac{d(v^* \rho_f h_f)}{dT} \right] \frac{dq}{dT} + \frac{\partial(v^*c)}{\partial T} \frac{\partial h_s}{\partial T} = 0 \tag{2}$$

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