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STUDIES IN MICROMERITICS

II. THE DEPOSITION OF PARTICLES IN CIRCULAR CONDUITS DUE TO THERMAL GRADIENTS

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II. THE DEPOSITION OF PARTICLES IN CIRCULAR CONDUITS
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October 1, 1961

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STUDIES IN MICROMERITICS
II. THE DEPOSITION OF PARTICLES IN CIRCULAR CONDUITS
DUE TO THERMAL GRADIENTS*

INTRODUCTION

Accurate sampling of particulates in gaseous effluents is necessary to audit and control airborne wastes released from installations processing toxic materials. In practice, sampling probes may not be located at points readily accessible to personnel, and in such cases a sample delivery line is required to transport the aerosol stream to a more convenient location. For proper evaluation of the validity of the sample, the fractional loss of suspended particles on the wall of the delivery line must be known. Hence, the loss due to each deposition mechanism must be considered.

If the region outside the delivery line is cooler than the sampled gas, heat will be lost from the line. The transfer of heat from the outside of a conduit is accompanied by temperature gradients within the gas stream which cause suspended particles to migrate toward the wall. Small particles contacting the wall adhere, resulting in a loss of particles from the gas stream. Although the present paper treats deposition due to thermal gradients alone, other modes of deposition such as gravitational settling and fluid turbulence should not be overlooked in analysis of the total loss to the wall.⁽¹⁾

PURPOSE

The objective of this paper is to present a simplified model and the derived equations for aerosol deposition on a conduit wall due to the thermal gradients resulting from the transfer of heat to the surroundings.

* This report is the second of a series of reports, "Studies In Micromeritics". The first report was "Particle Deposition in Conduits as a Source of Error in Aerosol Sampling", HW-65308, May 12, 1960.

SUMMARY

The deposition of particles from turbulent gas streams due to thermal gradients was predicted using a simplified flow model. In the model, particle concentration was assumed constant in the turbulent region. The particle deposition velocity was taken to be the radial velocity of thermal repulsion in the laminar sublayer. Temperature gradients in the laminar sublayer were calculated for constant wall temperature using the Reynold's analogy.⁽³⁾ The loss magnitude of suspended particles from loss due to thermal deposition is not generally great, and is most important for submicron particles.

THERMAL GRADIENTS AND PARTICLE MOVEMENT

In the following derivation a flow model is assumed in which two zones exist: a laminar sublayer near the pipe wall ($y^+ \leq 5$) and a turbulent region extending from the center of the conduit to the edge of the laminar sublayer. In the turbulent region eddy diffusion is assumed to be great enough so that the profile of the concentration can be taken to be flat. Near the wall, in the laminar sublayer, the temperature gradient is obtained from the velocity profile according to the Reynold's analogy. The deposition velocity at a given position downstream is then taken to be the radial velocity of thermal repulsion at the edge of the laminar sublayer.

Consider a differential element of a circular conduit as shown in Figure 1. The symbols used are defined at the end of the report.

FIGURE 1

Differential Element of Conduit

The heat input to the element is given by $\frac{\pi}{4} d_w^2 U C_p \rho (T_b - T_B)$. Based on the assumption that physical properties are constant, the heat output is equal to

$$\frac{\pi}{4} d_w^2 U C_p \rho (T_b + dT_b - T_B) + h\pi d_w (T_b - T_w) dX.$$

For steady state conditions input equals output; hence,

$$\frac{\pi}{4} d_w^2 U C_p \rho (T_b - T_B) = \frac{\pi}{4} d_w^2 U C_p \rho (T_b + dT_b - T_B) + h\pi d_w (T_b - T_w) dX. \quad (1)$$

After simplification, Equation (1) becomes:

$$\frac{dT_b}{(T_b - T_w)} = - \frac{4hdX}{d_w \rho U C_p} \quad (2)$$

For the case where the wall temperature, T_w , is constant Equation (2) can be integrated between $X = 0$ and $X = X$, giving

$$\ln \frac{T_b - T_w}{T_o - T_w} = - \frac{4hX}{d_w \rho U C_p} \quad (3)$$

The dimensionless quantity $\frac{h}{\rho U C_p}$ is recognized as the Stanton number which, according to the Reynold's analogy, is equal to one-half the Fanning friction factor. (2) The Reynold's analogy is a good approximation for the common gases which have Prandtl numbers near unity. Replacing $\frac{h}{\rho U C_p}$ by $\frac{f}{2}$, equation (3) simplifies to

$$\ln \frac{T_b - T_w}{T_o - T_w} = - \frac{2fX}{d_w} \quad (4)$$

from which

$$\frac{T_b - T_w}{T_o - T_w} = e^{-\frac{2fX}{d_w}} \quad (4a)$$

For a flowing fluid having a Prandtl number equal to unity, the temperature distribution and the velocity distribution will be identical. (2)

Hence,

$$\frac{U_{\delta}}{U} = \frac{T_{\delta} - T_w}{T_b - T_w} \quad (5)$$

from which the temperature drop across the laminar sublayer is

$$T_{\delta} - T_w = (T_b - T_w) \frac{U_{\delta}}{U} \quad (6)$$

Substituting $(T_b - T_w)$ from Equation (4a) into Equation (6) gives

$$T_{\delta} - T_w = \frac{U_{\delta}}{U} (T_o - T_w) e^{-\frac{2fX}{d_w}} \quad (7)$$

The velocity gradient in the laminar sublayer is constant, implying that the temperature profile is also linear. Hence, the radial temperature gradient for $y^+ \leq 5$ may be expressed as

$$-\frac{\partial T}{\partial r} = \frac{T_{\delta} - T_w}{\delta} \quad (8)$$

Substituting $T - T_w$, the temperature drop across the laminar sublayer, from Equation (7) into Equation (8) gives

$$-\frac{\partial T}{\partial r} = \frac{U_{\delta}}{\delta U} (T_o - T_w) e^{-\frac{2fX}{d_w}} \quad (9)$$

The ratio $\frac{U_{\delta}}{\delta}$ is constant for a given flow condition and equal to $\frac{U Re f^{(3)}}{2d_w}$.

Substituting $\frac{U Re f}{2d_w}$ for $\frac{U_{\delta}}{\delta}$ in Equation (9) gives

$$-\frac{\partial T}{\partial r} = \frac{Re f (T_o - T_w) e^{-\frac{2fX}{d_w}}}{2d_w} \quad (10)$$

The radial velocity of thermal repulsion for a particle suspended in the laminar sublayer is related to the temperature profile according to⁽¹⁾

$$U_{tr} = - \frac{3\mu K_g K_m}{2(2K_g + K_p) \rho T} \frac{\partial T}{\partial r} \quad (11)$$

Substituting $-\frac{\partial T}{\partial r}$ from Equation (10) into Equation (11) gives

$$U_{tr} = \frac{3f\mu K_g K_m \text{Re}(T_o - T_w)e^{-\frac{2fX}{d_w}}}{4(2K_g + K_p) \rho T d_w} \quad (12)$$

Equation (12) gives the radial velocity of a particle located in the region $y^+ \leq 5$ as a function of distance from the pipe inlet, the fluid and particle properties, and the flow conditions. Fully developed flow has been assumed to exist over the entire length.

PARTICLE LOSS

In the following treatment the radial variation of particle concentration in the turbulent region ($y^+ \leq 5$) is assumed to be negligible. This would be a good approximation if the particle transfer rate to the wall is low or if the eddy diffusivity in the region $y^+ \leq 5$ were high. It has also been assumed that the rate of transfer of particles into the laminar sublayer is equal to the transfer of particles to the wall. This is obviously true only at the entrance where the concentration profile is flat, and it will be approximately true downstream provided the concentration in the laminar sublayer is not a strong function of the radial position. A third assumption was that all particles contacting the wall become permanently attached, a realistic assumption for particles smaller than several microns in diameter.

A particle input and output balance on the differential element shown in Figure 1 leads to

$$\frac{dC}{C} = - \frac{3f K_g K_m (T_o - T_w)e^{-\frac{2fX}{d_w}} dX}{(2K_g + K_p) T_\delta dw} \quad (13)$$

In Equation (13), T_δ is the temperature at the edge of the laminar sublayer which is a function of X , the distance downstream from the inlet. Rearranging Equation (7) gives

$$T_\delta = T_w + \frac{U_\delta}{U} (T_o - T_w) e^{-\frac{2fX}{d_w}} \quad (7)$$

The ratio $\frac{U_\delta}{U}$ is equal to $5\sqrt{\frac{f}{2}}$ (3), hence Equation (7) may be transformed to

$$T_\delta = T_w + 5\sqrt{\frac{f}{2}} (T_o - T_w) e^{-\frac{2fX}{d_w}} \quad (14)$$

If T_δ is substituted from Equation (14) into Equation (13) we get

$$\frac{dC}{C} = - \frac{3f K_g K_m (T_o - T_w) e^{-\frac{2fX}{d_w}}}{(2K_g + K_p) d_w \left[T_w + 5\sqrt{\frac{f}{2}} (T_o - T_w) e^{-\frac{2fX}{d_w}} \right]} \quad (15)$$

Equation (15) may now be integrated between $C = C_o$ and $C = C_\infty$, and between $X = 0$ and $X = X$, giving

$$\ln \frac{C_\infty}{C_o} = - \frac{3f K_g K_m}{(2K_g + K_p) d_w 5\sqrt{\frac{f}{2}}} \left\{ X - \frac{d_w}{2f} \ln \frac{[T_w e^{\frac{2fX}{d_w}} + 5\sqrt{\frac{f}{2}} (T_o - T_w)]}{[T_w + 5\sqrt{\frac{f}{2}} (T_o - T_w)]} \right\} \quad (16)$$

Equation (16) relates the particle concentration to the conduit length, X .

It may be simplified to apply to special conditions. For $\frac{X}{d_w}$ greater than about 100, $T_w e^{\frac{2fX}{d_w}}$ will be much larger than $5\sqrt{\frac{f}{2}} (T_o - T_w)$. Neglecting the latter quantity Equation (16) reduces to

$$\ln \frac{C_\infty}{C_o} = - \frac{3 K_g K_m}{2(2K_g + K_p) 5\sqrt{\frac{f}{2}}} \ln \left[1 + \frac{5\sqrt{\frac{f}{2}} (T_o - T_w)}{T_w} \right] \quad (17)$$

C_∞ is the particle concentration existing at a distance beyond about 100 diameters downstream from the inlet.

Under most conditions of interest, the quantity $\frac{5\sqrt{f}}{2} \frac{(T_o - T_w)}{T_w}$ is

small compared to unity. Hence in the Taylor's series expansion of

$$\ln \left[1 + \frac{5\sqrt{f}}{2} \frac{(T_o - T_w)}{T_w} \right],$$

second and higher powers of $\frac{5\sqrt{f}}{2} \frac{(T_o - T_w)}{T_w}$ may be neglected so that approximately

$$\ln \left[1 + \frac{5\sqrt{f}}{2} \frac{(T_o - T_w)}{T_w} \right] = \frac{5\sqrt{f}}{2} \frac{(T_o - T_w)}{T_w} . \quad (18)$$

Substituting Equation (18) into Equation (17) yields

$$\ln \frac{C_\infty}{C_o} = - \frac{3 K_g K_m (T_o - T_w)}{2(2K_g + K_p) T_w} \quad (19a)$$

or equivalently,

$$\frac{C_\infty}{C_o} = \exp \left[- \frac{3 K_g K_m (T_o - T_w)}{2(2K_g + K_p) T_w} \right] \quad (19b)$$

C_∞ represents the particle concentration after the aerosol has passed through an infinitely long conduit. Practically, this concentration is reached at a distance downstream corresponding to $\frac{X}{d_w}$ equal to about 100. For a conduit having a diameter of one-inch, this implies that significant thermal deposition would not occur further than about eight feet from the inlet.

An expression identical to Equation (19a) results if Equation (13) is integrated from $X = 0$ to $X = \infty$, and from $C = C_o$ to $C = C_\infty$, taking T_δ to be T_w .

DISCUSSION

According to Equation (19b), the total particle loss to the wall increases with K_g , K_m , and $(T_o - T_w)$. Any increase in K_p or T_w would decrease the fractional loss of suspended particles.

The thermal conductivities of the common gases increase with increasing temperature. The highest values of thermal conductivity are associated with the lightest gases, hydrogen and helium. K_g ranges from 3.47×10^{-5} for CO_2 at $0^\circ C$ to about 7.03×10^{-4} for hydrogen at $300^\circ C$. (4)

In situations where the size of the particle approaches the mean free path of the molecules in the suspending gas, the particles encounter less resistance than predicted by Stokes's law. The Cunningham factor is the ratio of the Stokes's law force to the actual force, and increases from unity to a value dependent on the relative size of the particle and the molecular mean free path in the gas. For air at atmospheric pressure and at $100^\circ C$, K_m has a value of 1.022 for 10 micron diameter particles. The value for 0.1 micron diameter particles under the same conditions is 3.61. (4)

The thermal conductivity of the aerosol particles, K_p , depends primarily on its chemical composition. For homogeneous solids, thermal conductivities vary from about 0.002 for glass to about 0.85 for copper. Excluding the metals, liquids generally have conductivities lower than the value given for glass.

The dependence of the deposition on the temperature difference $(T_o - T_w)$ demonstrates that if the line were operated isothermally, no deposition would occur. For negative values of $(T_o - T_w)$, the equation predicts a concentration increase as the aerosol passes through a duct. Although this is not possible, thermal gradients directed toward the center of the stream would decrease the deposition rate due to other mechanism such as Brownian diffusion and turbulent impaction.

The magnitude of the particle loss due to thermal deposition can be assessed to a limited extent by calculation $\frac{C}{C_o}$ for a typical case. Arbitrarily,

a system was chosen in which 0.1 micron diameter aerosol particles were being drawn through a one-inch diameter tube. An inlet temperature of 200 C and a wall temperature of 50 C were assumed. The value of K_p was taken to be that of glass, an average value being 0.002. ⁽²⁾ For these conditions the thermal conductivity of air was estimated to be 8.26×10^{-5} . ⁽²⁾ K_m was taken as 3.2. ⁽⁴⁾ Hence,

$$\frac{C_{\infty}}{C_0} = \exp \left[- \frac{(3) (8.25 \times 10^{-5}) (3.2) (150)}{(2) (0.00216) (323)} \right] = \exp(-0.085) = 0.92$$

We conclude that a maximum of 8 per cent of the suspended particulates would be deposited on the wall. For the 1-inch tube this deposition would occur within the first eight feet.

CONCLUSIONS

Thermal gradients resulting from the transfer of heat from the outside of a conduit will cause deposition of suspended particles. If the direction of the gradient were reversed (gas stream heated) thermal deposition would be eliminated and the force of thermal repulsion would reduce the deposition due to other mechanisms. The magnitude of the particle loss due to thermal gradients is not generally great.

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The author is indebted to L. C. Schwendiman for his helpful criticism of this work.

NOMENCLATURE

- C = particle concentration in gas, $\frac{\text{particles}}{\text{cm}^3}$
- C_p = heat capacity of gas, $\frac{\text{Cal}}{\text{g}^\circ\text{K}}$
- d_w = inside diameter of conduit, cm
- e = base of natural logarithms, dimensionless
- f = Fanning friction factor, dimensionless
- h = inside heat transfer coefficient, $\frac{\text{cal}}{\text{cm}^2 \text{ sec } ^\circ\text{C}}$
- K_g = thermal conductivity of gas, $\frac{\text{cal cm}}{\text{sec cm}^2 ^\circ\text{C}}$
- K_m = Cunningham's correction factor for Stokes's law, dimensionless
- K_p = thermal conductivity of particle, $\frac{\text{cal cm}}{\text{sec cm}^2 ^\circ\text{K}}$
- r = radial distance measured from pipe axis, cm
- Re = Reynold's number = $\frac{\rho d_w U}{\mu}$, dimensionless
- T = absolute temperature, $^\circ\text{K}$
- T_b = bulk temperature of gas, $^\circ\text{K}$
- T_B = arbitrary base temperature, $^\circ\text{K}$
- T_o = inlet temperature of gas, $^\circ\text{K}$
- T_w = temperature of conduit wall, assumed constant, $^\circ\text{K}$
- T_δ = temperature at edge of laminar sublayer, $^\circ\text{K}$
- U = average gas velocity, $\frac{\text{cm}}{\text{sec}}$
- U_{tr} = particle velocity due to thermal repulsion, $\frac{\text{cm}}{\text{sec}}$
- U_δ = gas velocity at edge of laminar sublayer, $\frac{\text{cm}}{\text{sec}}$

NOMENCLATURE (contd.)

X = distance downstream from inlet, cm

y = radial distance measured from pipe wall, cm

y^+ = dimensionless distance parameter $= \frac{y}{d_w \text{ cm}} \text{ Re} \sqrt{\frac{f}{2}}$,

δ = thickness of laminar sublayer, cm

ρ = gas density, $\frac{\text{g}}{\text{cm}^3}$

μ = gas viscosity, $\frac{\text{g}}{\text{cm sec}}$

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