Aerosol Collection in the Jet Region of Fluidized Filters

A method is proposed for calculating aerosol collection in the jet region of fluidized filters with sieve plate distributors. With the use of the model proposed earlier by Lefroy and Davidson and a new correlation for the single-collector efficiency, which was established as part of this study, a compartment-to-compartment procedure was developed for estimating aerosol collection. The results were compared with experimental data for model validation.

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SCOPE

Experimental data of aerosol collection in fluidized beds are characterized by the great disparity among results reported by various investigators. Consequently, it is difficult to base design considerations on experimental data alone. Theoretical models that can be used to predict the extent of collection under a given set of operating conditions are therefore required.

In recent years, Peters et al. (1982) and Ushiki and Tien (1984) have presented methods for calculating aerosol collection in fluidized filters. Both studies relied on the use of the bubble assembly model of gas-solid fluidization although they differed somewhat in the detailed description of the bed structure and in the methods used for estimating aerosol collection. Neither method, however, made allowance that the region immediately above the distributor plate in a fluidized bed may exhibit behavior significantly different from the rest of the bed. This region, commonly known as the jet region, often offers high heat and/or mass transfer rates. Similarly, in aerosol filtration, the rate of aerosol collection has been found to be much higher in the jet region of a fluidized filter as compared with that in the rest of the filter (Knettig and Beeckmans, 1974; Nienow and Killick, 1983).

For a fluidized bed with sieve plate distributor, the regions immediately above each orifice of the distributor plate may be approximated as a spouted bed. Based on this consideration, a method of aerosol collection in the jet region was proposed. This method considered the jet region to be composed of a series of compartments of circular cross section. Each compartment is assumed to be of two phases, a gas jet core surrounded by an annular dense phase. Overall aerosol collection was estimated by considering collections in both phases. The effect due to gas flow from the core to the annular dense phase and that due to solid flow from the dense phase to the jet were also accounted for.

The porosity of the annular dense phase is similar to that of a fixed bed. On the other hand, because of relatively low particle concentration in the jet, the porosity of certain parts of the jet is close to unity. For estimating the extent of aerosol collection in both phases, a new correlation of the single collector efficiency of filter grains, valid from $\epsilon = 0.4$ to $\epsilon = 1.0$ was established. This correlation was based on the fixed-bed data collected by Takahashi et al. (1984) and single-sphere results reported by Schuch and Loffler (1978). The effect of the fluid inertia was also considered in the correlation.

CONCLUSIONS AND SIGNIFICANCE

A method is proposed for calculating aerosol collection in the jet region of fluidized bed filters. The method employs the Lefroy and Davison model of spouted beds and calculates the extent of aerosol collection by a compartment-to-compartment procedure. To estimate the collection efficiencies of the individual collectors (fluidized particle) in both the jet and dense phases, a

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new correlation that incorporates both fixed-bed and single-sphere data was developed. The validity of the method was substantiated through comparisons with experimental data.

Theory

The jet region of a fluidized bed with sieve plate distributor can be represented by a cylindrical unit of height H (jet height) and diameter D_b, consisting of a jet of diameter D_j issuing from an orifice surrounded by an annular dense phase with porosity ϵ_o, the porosity of the unfluidized bed. There is a continuous flow of gas from the jet to the dense phase and a flow of solid in the reverse direction, as depicted in Figure 1.

If the jet region is assumed to be similar to a spouted bed, the results of Lefroy and Davidson (1969) on spouted beds can be readily applied. In terms of the Lefroy and Davidson model, the geometry of the jet region is characterized by the jet height, H, and the jet diameter, D_j. The flow behavior is described by the gas and solid velocities, u and v, in both the jet and dense phases. For a given set of operating conditions—namely, given the total gas velocity, u, the type of distributor plate (area per orifice, s), and the size of the fluidized particles, d_c—empirical correlations that can be used to predict H and D_j were established. On the other hand, from a consideration of mass and momentum balances, equations were derived whose solutions give u_a, u_j, v_a, v_j, as well as the jet porosity, ϵ_j, where the subscripts j and a respectively denote the jet and dense phase as functions of the distance from the distributor plate. Details of these empirical correlations and equations for the velocities and ϵ_j are given in the Appendix.

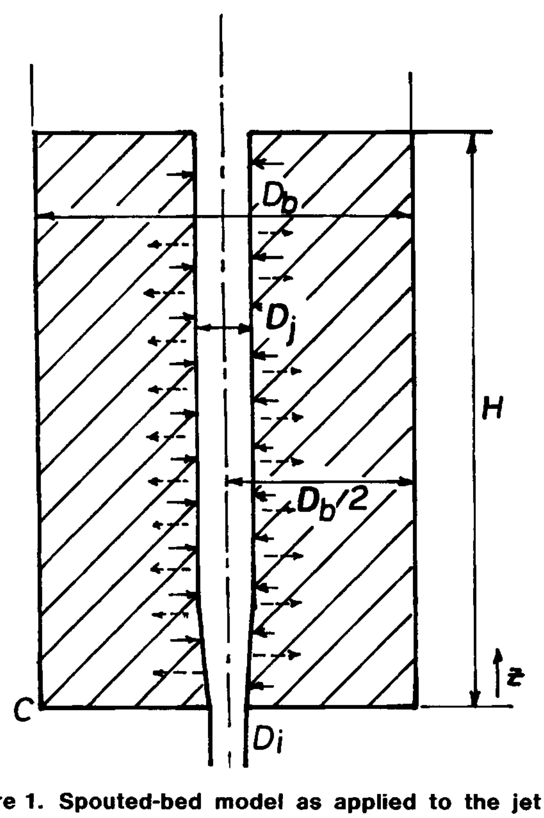

Figure 1. Spouted-bed model as applied to the jet region.
——→ Solid flow
– – – → Gas flow

The jet region model of Lefroy and Davidson predicts a continuous change in both the velocities and porosity along the axial direction. This fact necessitates, for calculating aerosol collection, the adoption of the compartment-to-compartment approach that was used earlier (Peters et. al., 1982; Ushiki and Tien, 1984). The computation scheme is described below.

For purposes of calculation, the jet region is divided into N compartments such that the height of each compartment, Δz, is equal to H/N. Within each compartment, the gas and solid velocities u_j, u_a, v_j, v_a, and the jet porosity, ϵ_j, may be considered as constant; that is, they are assumed to be the same as those corresponding to $z = j \cdot \Delta z$ for the jth compartment. The interphase flow (both gas and solid) occurs between the compartments. The quantities are:

- Gas flow from the jet to the dense phase between the $(i-1)$th and ith compartments

$$\frac{\pi}{4}(D_b^2 - D_j^2)(u_{a_i} - u_{a_{i-1}})\epsilon_o$$

- Solid flow from the dense phase to the jet between the $(i-1)$th and the ith compartment

$$\frac{\pi}{4}(D_b^2 - D_j^2)(v_{a_i} - v_{a_{i-1}})(1 - \epsilon_o)$$

To estimate the extent of aerosol collection, the annular space may be treated as a slow-moving bed. Adopting the Happel model for characterizing the filter media structure, the profile of the aerosol concentration in the gas flowing through the annular space of the ith compartment is

$$c_{a_i} = (c_a)_{\text{in},i} \exp\left[-\frac{3(\eta_a)_i(1-\epsilon_o)}{2d_c} \cdot \Delta z\right] \quad (1)$$

where $(c_a)_{\text{in},i}$ is the influent aerosol concentration of the dense phase of the ith compartment. Equation 1 is obtained under the assumption that the unit collector efficiency of the dense phase, $(\eta_a)_i$, is constant throughout the entire compartment. For calculating the value of $(c_a)_{\text{in},i}$, note that the influent to the dense phase of the ith compartment results from combining the effluent of the dense phase of the $(i-1)$th compartment and the gas flow from the jet phase to the dense phase between the $(i-1)$th and the ith compartment. Accordingly, by mass balance

$$(c_a)_{\text{in},i} = [(u_{a_i} - u_{a_{i-1}})c_{j_{i-1}} + u_{a_{i-1}}c_{a_{i-1}}]/u_{a_i} \quad (2)$$

The porosity of the jet phase is relatively high; namely, considerably fewer fluidized particles are present in the jet phase than in the dense phase. For this reason, one may assume that the aerosol concentration within the jet phase of a given compartment is uniform. The extent of aerosol collection is given as

$$\frac{\pi}{4} D_j^2 u_{j_i} \epsilon_{j_i} (c_{j_{i-1}} - c_{j_i}) = \frac{3\pi}{8} \frac{D_j^2}{d_c} (1 - \epsilon_{j_i}) \Delta z (u_{j_i} - v_{j_i}) \cdot c_{j_i} \cdot \eta_{j_i} \quad (3)$$

After rearrangement, one has

$$c_{j_i} = c_{j_{i-1}} \Bigg/ \left[1 + \frac{3}{2} \frac{\Delta z}{d_c} \frac{1 - \epsilon_{j_i}}{\epsilon_{j_i}} \left(1 - \frac{v_{j_i}}{u_{j_i}} \right) \eta_{j_i} \right] \quad (4)$$

The effluent concentration of the filter can be found by combining the exit gas streams from the jet phase and the dense phase of the Nth compartment. c_{eff} is given as

$$c_{eff} = \left(\frac{D_j}{D_b} \right)^2 \frac{u_{j_N}}{u} \epsilon_{j_N} c_{j_N} + \left[1 + \left(\frac{D_j}{D_b} \right)^2 \right] \frac{u_{a_N}}{u} \epsilon_o c_{a_N} \quad (5)$$

A schematic diagram that demonstrates the calculation of aerosol collection is shown in Figure 2.

The prediction of the filter performance in the jet region therefore can be made from Eqs. 1–5. The gas and solid velocities in the jet and dense phases and the porosity of the jet phase corresponding to various compartments (or values of axial distance z) can be obtained from the equations given in the Appendix. In addition, the values of the single-collector efficiencies, η_a

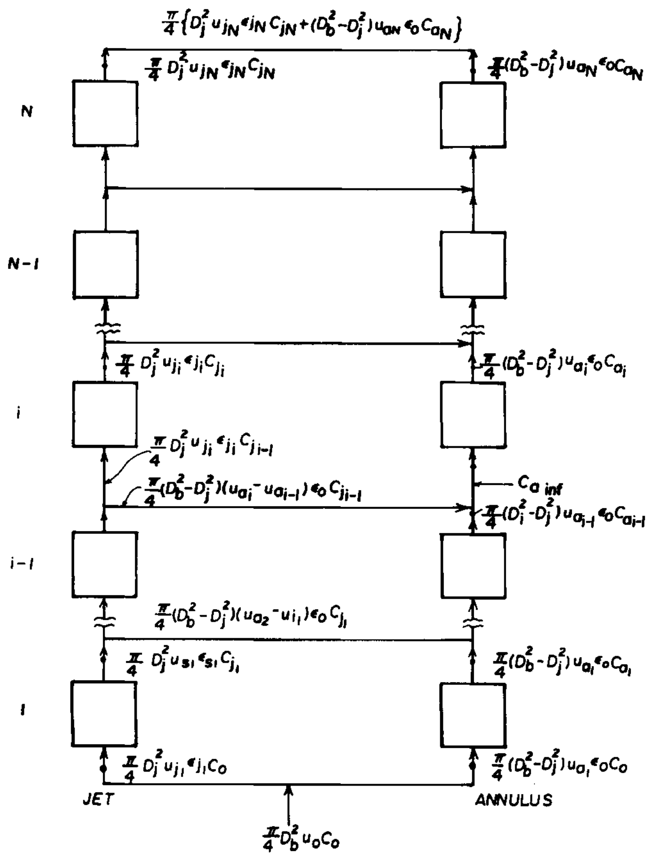

Figure 2. Aerosol balance on compartment-to-compartment calculations.

and η_j, are also required. These values are dependent upon a number of variables including the porosity. The porosity of the dense phase is approximately the same of that of the unfluidized bed (ϵ_o), while ϵ_j may vary from ϵ_o to unity depending upon the value of z. In order to account for these significant variations in porosity, a new correlation of the single-collector efficiency was established. Following the results of earlier studies, (Schuch and Loffler, 1978; Thambimuthu, 1980; D'Ottavio and Goren, 1983; Takahashi et al., 1985; Yoshida and Tien, 1985) a new correlation of the single-collector efficiency is developed and is given as

$$\eta = \left(\frac{N_{St_{eff}}}{N_{St_{eff}} + a} \right)^b \quad (6)$$

where the effective Stokes number is defined as

$$N_{St_{eff}} = \{[A(\epsilon)]^{0.9} + 6.1\,[1 - \exp(-0.0021\, N_{Re}^{1.257})]\epsilon^{-3/2}\} \cdot N_{St} \quad (7)$$

and

$$N_{St} = (c\rho_p d_p^2 |u - v|)/(18 \mu d_c) \quad (8)$$

$$A = \frac{6 - 6(1-\epsilon)^{5/3}}{6 - 9(1-\epsilon)^{1/3} + 9(1-\epsilon)^{5/3} - 6(1-\epsilon)^2} \quad (9)$$

with $b = 3.7$ and $a = 1.3$.

The Stokes number as defined above is based on the relative velocity between the collector and the gas streams, and can be used to estimate both η_j and η_a.

Model Prediction and Literature Data

A number of investigators have reported data on the performance of fluidized filters. Furthermore, some of these investigators have given detailed information on aerosol concentration profiles inside filter beds. These concentration profile measurements therefore provide a basis for validifying the proposed method for calculating aerosol collection in the jet region.

The experimental data against which the present method is tested are those reported by Doganoglu et al. (1978), Nienow and Killick (1983), and Tam (1982). The conditions under

Table 1. Summary of Experimental Conditions

	Investigator		
	Doganoglu et al. (1978)	Nienow and Killick (1983)	Tam (1982)
Collector substances	Glass spheres	Bronze shot	Silica sand
Collector size	1.00×10^{-4} m	4×10^{-4} m	4.61×10^{-4} m
Aerosol particles	DOP, Methylene blue	K Mn O_4	Di-2-ethylhexylsebacate
Aerosol particle size	1.15, 1.6×10^{-6} m (DOP) 1.2×10^{-6} m (Methylene blue)	0.7×10^{-6} m	21.0×10^{-6} m
Column dia.	0.15 m	0.15 m	0.152 m
Gas velocity	0.13 m/s	0.57 m/s	1.1 ~ 1.8 m/s

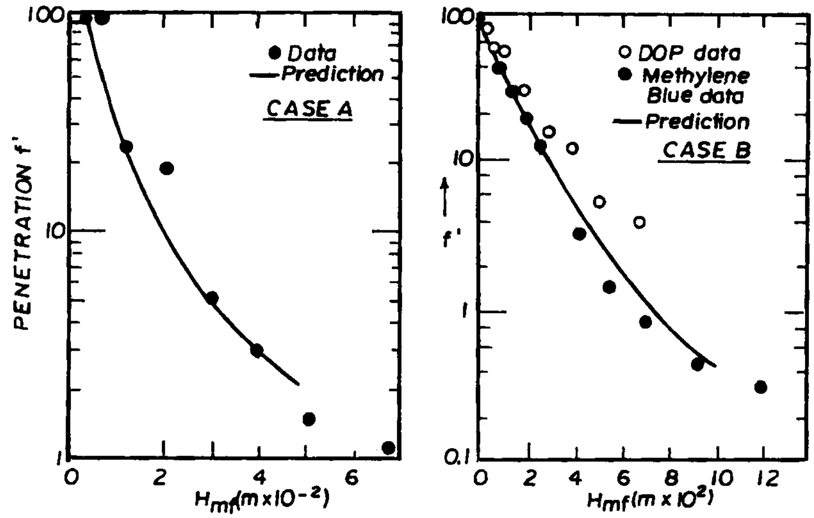

Figure 3. Comparison of prediction with data of Doganoglu et al (1978).
Case A: Penetration of 1.6×10^{-6} DOP aerosol through fluidized bed of collector A; $u = 0.13\ m \cdot s^{-1}$.
Case B: Penetration through bed of collector A; $u = 0.13\ m \cdot s^{-1}$.

which these experiments were carried out can be summarized in Table 1. The comparisons between experiments and predictions are shown in Figure 3 and Tables 2 and 3.

As shown in Figure 3, the agreement with the results of Doganoglu is rather good for both large and small fluidized particles. The aerosols used in Doganoglu's work were of two kinds, liquid aerosols of dioctyl phthalate (DOP), and solid aerosols of methylene blue. When solid aerosols were used in measurement, the fluidized particles were coated with a nonvolatile liquid.

Table 2. Comparison of Predictions with Data of Nienow and Killick (1983)

Type of Distribution*	Jet Height** Pred.	Total Collection Efficiency Pred.	Total Collection Efficiency Exp.†
2	2.46	0.907	0.50
3	1.80	0.861	0.40
4	2.46	0.917	0.29
5	4.761	0.973	0.25
6	1.6	0.841	0.045

*As defined by Nienow and Killick
**Based on $\phi = 30°$ in 10^{-2} m
†Read from the smoothed curve given in Fig. 7 of Nienow and Killick at a bed height equal to jet height

Table 3. Comparison of Predictions with Data of Tam (1982)

d_p 10^{-6} m	Penetration in Jet Region, c_{eff}/c_{in} Pred.*	Tam**
	$u = 1.1$ m/s	
1.2	0.456	0.433
1.6	0.251	0.148
	$u = 1.8$ m/s	
1.2	0.519	0.832
1.6	0.346	0.268

*Assuming that $\rho_p = 1.0$ kg/m^3
**Values from Tam, Table 3.7

Accordingly, one may assume that there was no bouncing off of impacting aerosols from collectors (fluidized particles).

The comparisons between predictions and the data of Nienow and Killick are given in Table 2. It is obvious that the predictions are substantially different from the reported data. Two possible explanations may be offered. First, the rest angle, ϕ, which is required to predict the jet diameter (see Eq. A8), was not known and was assumed to be 30°. More important, the possibility of the bouncing off of impacting particles from collectors in the jet region was not considered. The more recent work of Yoshida and Tien (1984) has found that at $N_{St} = 10^{-1}$, less than 10% of impacting aerosols in a fixed bed are collected. On the other hand, the single-collector efficiency correlation of Eq. 6 assumes complete adhesion of impacting aerosols. The difference between predictions and experiments in this case, therefore, is not surprising.

The results of comparison with Tam's data are given in Table 3. For the four cases considered, good agreement in three cases was observed. However, since the jet penetration values reported by Tam are only estimations, care must be exercised in drawing any conclusions from these comparisons.

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Notation

A = function of porosity, Eq. 7
a, b = empirical constants, Eq. 6
c = Cunningham's correction factor
c_{in}, c_{eff} = influent and effluent aerosol concentrations
$(c_a)_i$ = effluent aerosol concentration of dense phase of ith compartment
$(c_j)_i$ = aerosol concentration of jet phase of ith compartment
$(c_a)_{in,i}$ = influent aerosol concentration in dense phase of ith compartment
D_b = diameter of basic unit representative of jet region
D_j = jet diameter
d_c = diameter of collectors (fluidized particles)

d_p = aerosol diameter
F_0, F_1, F_2, F_3 = defined by Eqs. A13a, A13b, A13c, and A13d, respectively
H = jet height
N = number of compartments
N_{St} = Stokes number, Eq. 8
$N_{St_{eff}}$ = effective Stokes number, Eq. 7
P_a = pressure in dense phase
s = cross-sectional area per unit orifice
u = gas velocity
u_a, u_j = gas velocity in dense and jet phase, respectively
u_{mf} = minimum fluidization velocity
v_a, v_j = solid velocity in dense and jet phase, respectively
z = axial distance

Greek letters

β = factor to account for momentum transfer between solid and gas in jet phase
ϵ = porosity
ϵ_o, ϵ_j = porosity of dense and jet phase, respectively
ϕ = rest angle
η = single-collector efficiency
$(\eta_a)_i, (\eta_i)_i$ = single-collector efficiency in dense and jet phase of ith compartment
ρ_c = density of fluidized particles
ρ_p = aerosol particle density
μ = viscosity of gas

Appendix: Application of LeFroy and Davidson Model of Spouted Beds

The model of Lefroy and Davidson (1969) provides an approximate estimation of the solid and gas velocities along the axial directions in both the jet region and the dense phase. The gas velocity and pressure in the annular space, u_a and p_a, are given as

$$u_a = u_{mf} \sin \frac{\pi z}{2H} \tag{A1}$$

$$p_a = \frac{2\rho_c g H(1-\epsilon_o)}{\pi} \cos\left(\frac{\pi z}{2H}\right) \tag{A2}$$

where H is the height of the jet and ϵ_o is the porosity of the dense phase, and ρ_c is the density of the grains. As an approximation, ϵ_o may be taken to be that of the bed in its unfluidized state.

To obtain the gas and solid velocity in the jet region, and the solid velocity in the dense phase, the total mass balance of gas and solid and the momentum balance of gas and solid in the jet region are considered. The equations are

Total Gas Balance

$$D_b^2 u = (D_b^2 - D_j^2)\epsilon_o u_a + D_j^2 \epsilon_j u_j \tag{A3}$$

Total Solid Balance

$$(D_b^2 - D_j^2)(1-\epsilon_o)v_a + D_j^2(1-\epsilon_j)v_j = 0 \tag{A4}$$

Momentum Balance of Gas in the Jet Region

$$\rho \frac{d}{dz}(\epsilon_j u_j^2) = -\epsilon_j \frac{dp_a}{dz} - \beta(u_j - v_j)^2 \tag{A5}$$

$$\rho_c \frac{d}{dz}[(1-\epsilon_j)v_j^2] = -(1-\epsilon_j)\frac{dp_a}{dz} - \rho_c g(1-\epsilon_j) + \beta(u_j - v_j)^2 \tag{A6}$$

where u_j, v_j, and v_a denote the gas velocity in the jet, solid velocity in the jet, and solid velocity in the annular space, respectively. β is a factor accounting for the transfer of momentum between gas and particles in the jet region. According to Lefroy and Davidson, β is given as

$$\beta = 0.33\rho \frac{1-\epsilon_j}{d_c \epsilon_j^{1.78}} \tag{A7}$$

To complete the description, it is necessary to know both the jet height and the jet diameter. Empirical expressions for both quantities have been given by LeFroy and Davidson. They are

$$(D_b^2 - D_j^2)\tan\phi = 1.675\, D_j^3 d_c^{-1} \tag{A8}$$

$$H = 1.86\, D_j^2 d_c^{-1} \tag{A9}$$

The value of D_b can be found from the following argument. From the total area of the distribution plate and the number of orifices, the area per orifice, s, can be readily calculated. D_b is given as

$$D_b = \left(\frac{4}{\pi}s\right)^{1/2} \tag{A10}$$

Assuming that the values of D_b, D_j, and H are known, u_a is given by Eq. A1. By combining Eqs. A1 and A3, an expression of $\epsilon_j u_j$ can be obtained. Substituting that expression and that of p_a (i.e., Eq. A2) into Eqs. A5 and A6, the following equations were obtained

$$\frac{d\epsilon_j}{dz} = \frac{F_2(z,\epsilon_j) + F_3(z,\epsilon_j,v_j) - F_1(z,\epsilon_j)}{F_0(z,\epsilon_j)} \tag{A11}$$

$$\begin{aligned}\frac{d[(1-\epsilon_j)v_j^2]}{dz} &= (1-\epsilon_j)g(1-\epsilon_o)\sin\frac{\pi z}{2H} \\ &\quad - g(1-\epsilon_j) + \frac{0.33\rho(1-\epsilon_j)}{\rho_c d_c \epsilon_j^{1.78}} \\ &\quad \cdot \left\{\frac{1}{\epsilon_j}\left[u\left(\frac{D_b}{D_j}\right)^2 - u_{mf}\left(\frac{D_o^2}{D_j^2} - 1\right)\sin\frac{\pi z}{2H}\right] - \sqrt{\frac{(1-\epsilon_j)v_j^2}{(1-\epsilon_j)}}\right\}^2\end{aligned} \tag{A12}$$

where

$$F_0(z,\epsilon_j) = \frac{-\rho}{\epsilon_j^2}\left[u\left(\frac{D_o}{D_j}\right)^2 - u_{mf}\left(\frac{D_b^2}{D_j^2} - 1\right)\sin\frac{\pi z}{2H}\right]^2 \tag{A13a}$$

$$\begin{aligned}F_1(z,\epsilon_j) &= \frac{\pi\rho}{H}\left[\frac{1}{\epsilon_j}\cos\left(\frac{\pi z}{2\pi}\right) \cdot u_{mf}^2\right. \\ &\quad \left. \cdot \left(\frac{D_b^2}{D_j^2} - 1\right)^2 \sin\frac{\pi z}{2H} - u_o\left(\frac{D_b}{D_j}\right)^2 u_{mf}\left(\frac{D_b^2}{D_j^2} - 1\right)\right]\end{aligned} \tag{A13b}$$

$$F_2(z, \epsilon_j) = \epsilon_j \rho_c g (1 - \epsilon_o) \sin \frac{\pi z}{2H} \quad \text{(A13c)}$$

$$F_3(z, \epsilon_j, v_j) = -\frac{0.33\rho(1-\epsilon_j)}{d_c \epsilon_j^{1.78}} \left\{ \frac{1}{\epsilon_j} \left[u_o \left(\frac{D_j}{D_b} \right)^2 - u_{mf} \left(\frac{D_b^2}{D_j^2} - 1 \right) \sin \frac{\pi z}{2H} \right] - \sqrt{\frac{(1-\epsilon_j) v_j}{1-\epsilon_j}} \right\}^2 \quad \text{(A13d)}$$

Equations A11 and A12 have v_j and ϵ_j as their dependent variables. More conveniently, ϵ_j and $(1 - \epsilon_j)\, v_j^2$ can be considered as the two dependent variables. The initial conditions that are required for the solution of these two equations are

$$\epsilon_j = 1 \quad \text{and} \quad (1 - \epsilon_j) v_j^2 = 0 \quad \text{at} \quad z = 0 \quad \text{(A14)}$$

The use of the above initial conditions implies that v_j at $z = 0$ is left undefined. However, by virtue of Eq. A4 and the argument that particles immediately adjacent to the distribution plate do not move along axial direction, v_j at $z = 0$ may be taken to be zero.

In summary, the solution of Eqs. A11 and A12 subject to the initial conditions of Eq. A14 gives the values of v_j and ϵ_j as functions of z. These results together with Eqs. A3 and A4 then give a complete description of the fluid mechanical behavior of the jet region. There is, however, an inconsistency in the formulation. With the assumption of constant D_j and with the flow of solid from the annular space to the jet, the dense phase porosity cannot be a constant as assumed here. However, since the amount of solid flow is relatively modest, this inconsistency does not introduce significant error, at least not in calculating aerosol collection.

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