REFINEMENT OF SCREEN-TYPE DIFFUSION BATTERY FOR FAST MEASUREMENT AND ITS VALIDATION BY NUMERICAL SIMULATION

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Abstract. Screen-type diffusion battery (SDB) system was refined in screen stacking for fast measurement. The performance in size analysis was confirmed by numerical simulation. Stacking was examined in cumulated number of screens and stages. As the results, the optimal stacking condition was performed when the cumulated number of screens was selected as equidistance parallel lines of penetration at each stage. In consideration of bimodal particle size distribution, 5 stages model with 1, 4, 16 and 64 screens of 635-mesh would achieve optimum performance for the fastest measurement. The newly optimized system showed equivalent performance as the traditional 11 stages model. The SDB system, which is capable of shortening measurement time to half, will be more optimal model in the field measurements.

Key words: screen-type diffusion battery, shortening time, numerical simulation

1. Introduction

Screen-type diffusion battery has been used to measure size distribution of airborne particles. It measures the concentration of penetrating particles in each stage of diffusion battery. Assuming that the particle concentration in the sample air is stable, the diffusional particle size is estimated by unfolding the penetration data of stages. Unfortunately the stability for concentration of airborne particles lasts only a short time, especially in actual environment. For getting more actual particle size distribution, prompt sampling is better to avoid the fluctuation of particle concentration. Previously, we reported the fast measurement system with SDB/CNC (Yamada *et al.*, 2000). The system was improved mainly in hardware consequence. In the same configuration as the traditional system, the measuring time had been shortened to half.

In this paper, the SDB/CNC system was refined fundamentally for fast measurement. Furthermore the validation by numerical simulation was made for accuracy with comparison between traditional and newly system.

2. Materials and Method

2.1. Configuration for SDB

SDB is a user-configured system to provide screen type, stage numbers and sampling flow rate for specific purpose. Therefore many SDB systems have been proposed and used for particle size measurement. In this paper, three stacking patterns of screens were compared at the same simulated condition. Table 1 shows stacking condition based on an arithmetic progression, a geometric progression and an integral multiple of 5. The arithmetic progression

Table 1. Stacking condition for 3 different SDB models.

	No. of stage	Cumulated number of screens
Arithmetic progression	11	0, 1, 3, 6, 10, 15, 21, 28, 36, 45, 55
Geometric progression	8	0, 1, 2, 4, 8, 16, 32, 64
Integral multiple of 5	11	0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50

system is the commercial SDB system of TSI (Thermo Systems Inc.), and its stage number is 11 stages system. In this system, the maximum cumulated number of screen is 55, so that 55 screens are an index of maximum cumulated number of screen for the other system. Subsequently the shortening system was determined on the basis of the best stacking condition among them. The 635-mesh screen was used for all stacking conditions. This screen was selected due to the fact that is the finest screen available for sampling particles.

2.2 Simulation Analysis

The numerical simulations were performed to compare an original size distribution with the unfolded size distribution. When the particle size distribution was supposed to be a lognormal distribution, it was expressed by only two parameters, the count median diameter (CMD) and the geometric standard deviation (GSD). In the simulation, the particle number concentrations were used as 10000 cm^{-3} , but the results of simulation are independent of concentrations. According to the screen-type diffusion battery theory, the fractional penetration, P , of monodisperse aerosols through the screens can be expressed (Cheng and Yeh, 1980; Cheng *et al.*, 1980) as:

$$\log P = -n(A_0 Pe^{-2/3} + A_1 R^2 + A_2 Pe^{-1/2} R^{2/3}),$$

where

n = number of screens

$A_0 = 1.17B$

$A_1 = 0.434B/\kappa$

$A_2 = 0.539B/\kappa^{1/2}$

$B = 4\alpha h/\pi(1-\alpha)d_f$

$\kappa = -0.5\ln(2\alpha/\pi) + (2\alpha/\pi) - 0.75 - 0.25(2\alpha/\pi)^2$, the hydrodynamic factor

$R = d_p/d_f$, the interception parameter

d_p = particle diameter

d_f = screen wire diameter

$Pe = Ud/D$, the Peclet number

U = superficial velocity in the diffusion battery

$D = kTC/3\pi\mu d_p$, the diffusion coefficient of the particle

k = Boltzman constant

T = the absolute temperature

C = slip correction

μ = fluid viscosity

h = thickness of the screen

α = solid volume fraction of the screen.

Calculation conditions were fixed as 4000 cm³/min for the sampling flow rate, 20 °C for the temperature, and 101 kPa for the pressure. Then the penetration data were analyzed by our NIRS (National Institute of Radiological Sciences) unfolding code, in which a size range of 1-1000 nm was divided into 48 size intervals throughout simulations.

The unfolding results are depends on iterations (Maher and Laird, 1985; Tohno *et al.*, 1996). In consequence of numerical simulations, many particle size distributions converged at before 1000 iterations by NIRS code. The differences between 1000 and more iterations showed percent of no more than 5 when iterations over 1000. Therefore, 1000 iterations will be enough to reconstructing particle size distribution. The time required for this calculation time is only a few second. In this paper, the maximum iteration was selected 1000 for all calculations.

3. Results and Discussion

3.1. Comparison among several stacking condition

Figure 1 shows typical results in the numerical simulations for unimodal and bimodal distributions. For the unimodal distribution, both arithmetic and geometric progression system could reconstruct the inputted original one satisfying between 5 nm and 150 nm. In a general way, a coarser screen is suitable for measuring a few nanometers rather than 635-mesh screen. Even though, these two systems could reconstruct until 5 nm with precision of

Figure 1. Typical reconstructed distribution for 3 different SDB models. Dotted line indicates the inputted original distribution. The unfolding distributions are arithmetic progression (○), geometric progression (●), and integral multiple of 5 (△). The inputted original distributions were following as: (a) CMD=5nm, GSD=1.3, (b) CMD=150nm, GSD=2, (c) 1:9 mixture of (a) and (b), (d) 9:1 mixture of (a) and (b).

an error within 5 percent for CMD and GSD values. Considering 5 nm as a lower limit for counting particle by CNC (Condensation Nuclei Counter) in general, these two systems could be sufficient for measuring particle size distribution in actual environment. The other one system failed to reconstruct the inputted original distribution especially at a few nanometers regions. It could be because the cause of this case that the penetration data of one screen as a few nanometers lacked. As a result, it would be better for analysis of a few nanometers that the one screen was selected for the first stage. For the bimodal distributions, the reconstructed results showed no significant differences existed with unimodal one. From these results, both arithmetic and geometric progression systems were sufficient stacking system for SDB.

For considering the shortening stage model, interesting comparisons could be drawn between the arithmetic and geometric progression models concerning the number of stacking stages. The geometric progression system could unfold using only 8 stages model in comparison with the arithmetic one using 11 stages. These results suggested that the geometric progression could measure the particle size distribution with efficiency by lesser number of stacking stages. Figure 2 shows the fractional penetration for 3 stacking systems. For the geometric progression model, the penetration curves for each stage showed equidistance parallel lines during straight-line segments. On the other hands, two other systems did not show equidistance. The penetration curve for geometric progression model covered over a wide range of particle diameter rather than two other systems. Considering efficient reconstructing distribution of the geometric progression system, Fig. 2 suggested that the cumulated number of screens in each stage would be selected as giving the equidistance parallel lines. From these results, the geometric progression was adopted as a basic system in the shortening stage number.

Figure 2. Fractional penetrations for 3 different SDB models.

3.2. Consideration for shortening system

For the purpose of shortening the measurement time to half of the commercial SDB system, the number of stacking stage should be set a limit as less than 6. On the based of the penetration curves for geometric progression system in Fig. 2, two shortening models were selected. One of them was 5 stages model as 1, 4, 16, and 64 screens, and the other was 4 stages model as 1, 8, and 64 screens.

3.3. Comparison between traditional and shortening stage systems

Numerical experiments against several particle size distributions were performed to estimate the differences in unfolding distribution between the shortening and traditional models. Figure 3 shows typical results for them. For unimodal condition, notable differences among 3 systems were not observed between 5 and 150 nm. These three systems could reconstruct with precision of an error within 5 percent for CMD and GSD values. For bimodal conditions, both 11 and 5 stages models could reconstruct the inputted original distribution sufficiently. On the other hands, the 4 stages model sometimes failed to reconstruct the distribution, for example as Fig. 3d. It was one of the reasons that the data were short in the 4 stages models for reconstruction of such case. These results suggested that the shortening system was required at least 5 stages model to reconstruct the bimodal distribution. The traditional model could reconstruct the inputted original distribution more accurately rather than the shortening system in some cases. This is a consequence of getting greater number of data rather than the shortening systems. However, the differences between traditional and 5 stages models were not significant during the simulated condition. If particle condition is stable, the traditional and 8 stages of geometric models will be able to measure the particle size distribution more accurately in comparison with the shortening systems. Considering the fluctuation and the dispersion of a counting data in the field, this 5 stages model will achieve the sufficient unfolding distribution and the half time measurement in comparison with traditional 11 stages model.

Figure 3. Typical reconstructed distribution for the shortening SDB models in comparison with traditional SDB model. Dotted line indicates the inputted original distribution. The unfolding distributions are traditional model (○), 5 stages model (●), and 4 stages model (△). The inputted original distributions were following as: (a) CMD=5nm, GSD=1.3, (b) CMD=150nm, GSD=2, (c) 1:9 mixture of (a) and (b), (d) 9:1 mixture of (a) and (b).

When particle concentration is quite low, the counts spread out to each stage and decrease to a very small value. At that time an accuracy of unfolding decreases, because each count has a statistically large variance for lower count (Fukutsu *et al.*, 1999). Therefore lesser stages are expected as increasing count per each stage. Furthermore, lesser stages are expected fast measuring time with less fluctuation of the particle concentration. From these reasons, the accuracy of data for the shortening stage would be strongly expected as better rather than many stages system. This advantage for fast system will produce to measure more reasonable size distributions.

4. Conclusion

In order to refine the sizing system of SDB for fast measurement, several numerical simulations were performed. As the results, the geometric progression was concluded the most valid stacking system. On the basis of the geometric progression, shortening system was determined as 5 stages with 1, 4, 16 and 64 screens of 635-mesh. This shortening system performed equivalent analysis results and less than half measuring time as compared with the traditional 11 stages model. Therefore the newly system is the optimum SDB for fast measurement.

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