CHARACTERISTICS OF AN AEROSOL PHOTOMETER WHILE AUTOMATICALLY CONTROLLING CHAMBER DILUTION-AIR FLOW RATE

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Trials were conducted to determine those factors that affect the accuracy of a direct-reading aerosol photometer when automatically controlling airflow rate within an exposure chamber to regulate airborne dust concentrations. Photometer response was affected by a shift in the aerosol size distribution caused by changes in chamber flow rate. In addition to a dilution effect, flow rate also determined the relative amount of aerosol lost to sedimentation within the chamber. Additional calculations were added to a computer control algorithm to compensate for these effects when attempting to automatically regulate flow based on a proportional-integral-derivative (PID) feedback control algorithm. A comparison between PID-controlled trials and those performed with a constant generator output rate and dilution-air flow rate demonstrated that there was no significant decrease in photometer accuracy despite the many changes in flow rate produced when using PID control. Likewise, the PID-controlled trials produced chamber aerosol concentrations within 1% of a desired level.

Typically, the goal of an animal or human aerosol exposure is to create and maintain the concentration of the aerosol near a desired level throughout the exposure period. To achieve that goal, commercially available aerosol photometers can be useful for providing real-time concentration measurements and thus the ability to make adjustments to the concentration level during an exposure. These instruments give a nearly instantaneous reading and, with some units, are capable of producing a voltage output signal proportional to concentration. If that voltage signal is read by a computer, also used for controlling the flow rate of air through the exposure chamber, then an automatic feedback control system to regulate aerosol

concentrations by varying the amount of dilution air can be implemented. Such a system would be especially useful in the case where the aerosol generator output rate is not easily adjustable or varies in an unpredictable manner over time.

A number of reports indicate that aerosol photometers are not always accurate, especially when sensing an air volume that contains a mixture of dust types (O'Brien et al., 1989) or when the particle size distribution of the aerosol changes over time (Smith et al., 1987; Willeke & Baron, 1990). Furthermore, a continuous recording of photometer readings often exhibits a random or "stochastic" tendency because of incomplete mixing of aerosols in the dilution air and/or random fluctuations in the particle generation rate (O'Shaughnessy et al., 1996). Sensor data of this type complicate the ability of a computer control algorithm to make appropriate control decisions because of the uncertainty associated with individual readings.

Application of changes in flow rate through a chamber may also have a variety of effects on the resulting aerosol concentration. In some cases, increased flow may diminish concentrations by a dilution effect. However, increased flow may also reentrain settled dust if the velocity across surfaces increases substantially (Nicholson, 1988). Changes in dilution air may also cause a shift in the size distribution of the aerosol, and a corresponding change in photometer response, by changing the relative amounts of impaction and sedimentation of the aerosol within the chamber.

The design and characterization of inhalation exposure chambers have been well described in the literature. Furthermore, descriptions of various computerized feedback control systems developed to automatically adjust aerosol generator output rate to achieve a desired concentration in both animal and human exposure chambers have been published (Carpenter et al., 1979; Coggins et al., 1989; Crider et al., 1980; Hirano, 1987; O'Shaughnessy & Hemenway, 1994; O'Shaughnessy et al., 1996). However, the use of a computer to control the ventilation rate through a chamber has only been described by Wong and Moss (1996). In that study, software developed to control ventilation rates in large buildings was adapted for use in an inhalation exposure facility to provide known rates of preconditioned air to whole-body exposure chambers.

This research was instigated for the purpose of developing an automatic feedback control system to change dilution-air flow rate based upon information obtained from an aerosol photometer placed in the chamber. Under the assumption that photometer response would change relative to changes in flow rate, trials were performed to determine the appropriate mathematical compensations required to maintain an acceptable level of instrument accuracy.

METHODS

Chamber Description

A 1-m^3 stainless-steel inhalation chamber was used for all tests performed during this research (Hemenway & MacAskill, 1982). A dry aerosol

was generated with the use of a Wright dust feed (BGI, Inc., Waltham, MA) set to deliver a constant mass output rate and introduced into the main air flow duct leading into the chamber. A radioactive ^{63}Ni source applied to the inside of the main air duct served to reduce the static charge of the dust to its Boltzman equilibrium level. Two centrifugal blowers, located on both the upstream and downstream side of the chamber, allowed the operator to both manipulate flow rate, between 0 and 0.5 m^3/min, and the static pressure of the chamber by setting manual valves on the supply and exhaust side of the chamber. Prior to the addition of automation equipment, a Magnehelic gauge, connected to a Pitot-venturi flowmeter located in the supply air duct, measured chamber flow. This flow meter indirectly measured flow rate by indicating the velocity pressure of the air where flow rate is directly proportional to the square root of velocity pressure. A Roots meter (Model 1.5M125, Dresser Industries, Houston, TX) was used to calibrate the relationship between manometer deflection and chamber flow rate.

The particular dust used during this research, cristobalite, a free crystalline silicon dioxide compound, was chosen because of its use in ongoing inhalation studies conducted at the time of this research (Absher et al., 1992; Davis et al., 1998). Cristobalite has a density of 2.4 g/cm^3 with a morphology characterized by irregular-shaped particles. The bulk powder had a count median diameter (CMD) near 20 μm as determined by sizing with a light microscope and Porton–May reticule. However, as described later, the particular generating method and chamber configuration used in this study removed the larger particles so that the resulting mass median aerodynamic diameter (MMAD) of the cristobalite aerosol was less than 5 μm.

Chamber Automation

To automatically adjust the chamber dilution flow rate through the chamber, a pneumatic valve positioner was attached to a control valve placed in the supply duct (series 765 and 24000, respectively, H. D. Baumann Assoc. Ltd., Portsmouth, NH). The positioner was designed to adjust a pressure regulator given a 4- to 20-mA signal from a digital-to-analog (D/A) converter (PCI-20093W-1, Burr-Brown, Tucson, AZ) connected to a personal computer (PC). The resulting air pressure acted against a diaphragm attached to the control valve, which in turn pushed the valve stem down. Therefore, the signal from the D/A converter was proportional to valve position and hence flow rate through the chamber. To automate the measurement of the chamber flow rate, a differential pressure transducer (model PX170, Omega Engineering, Inc. Stamford, CT) was attached to the Pitot-venturi flowmeter and the resulting voltage signal was read by an analog-to-digital (A/D) converter (model AD520, Real-Time Devices, State College, PA) connected to the PC (Figure 1).

An aerosol photometer (HAM-DS model 1050, PPM, Inc., Knoxville, TN), located in a central position in the chamber, produced a voltage signal proportional to concentration that was also read by the A/D converter
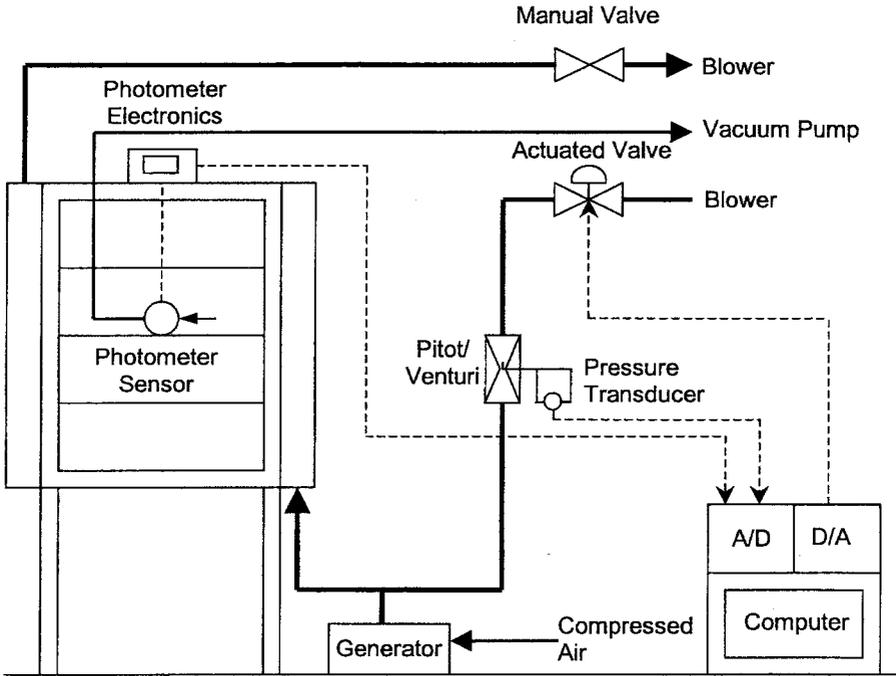
FIGURE 1. Automated chamber system schematic.

in the PC. This instrument was zeroed with injections of filtered air. Furthermore, a calibration device inserted into the view volume of the sensor allowed the operator to verify that the output range remained consistent from day to day. The sensors' optics were also cleaned on a daily basis with a compressed gas duster. Computer software was written to collect one photometer reading per second by the A/D converter. Consecutive averages of 15 such readings were calculated and both displayed on the computer monitor and placed in a computer file for future graphing and analysis with a spreadsheet. As shown in Figure 2, implementation of the automated dust control system required the application of an inner and outer control loop. The outer loop was responsible for the primary control task of determining the appropriate flow rate required to achieve a desired aerosol concentration as measured with the aerosol photometer. The inner control loop then acted to ensure that the air through the chamber flowed at the proper rate as indicated by the pressure transducer associated with the flow meter.

Sensor Accuracy

The accuracy of the aerosol photometer was measured by attaching a polycarbonate cowl to the aerosol photometer to support a filter cartridge directly in line with the view volume of the sensor (O'Shaughnessy & Hemenway, 1994). Therefore, all dust passing through the view volume of
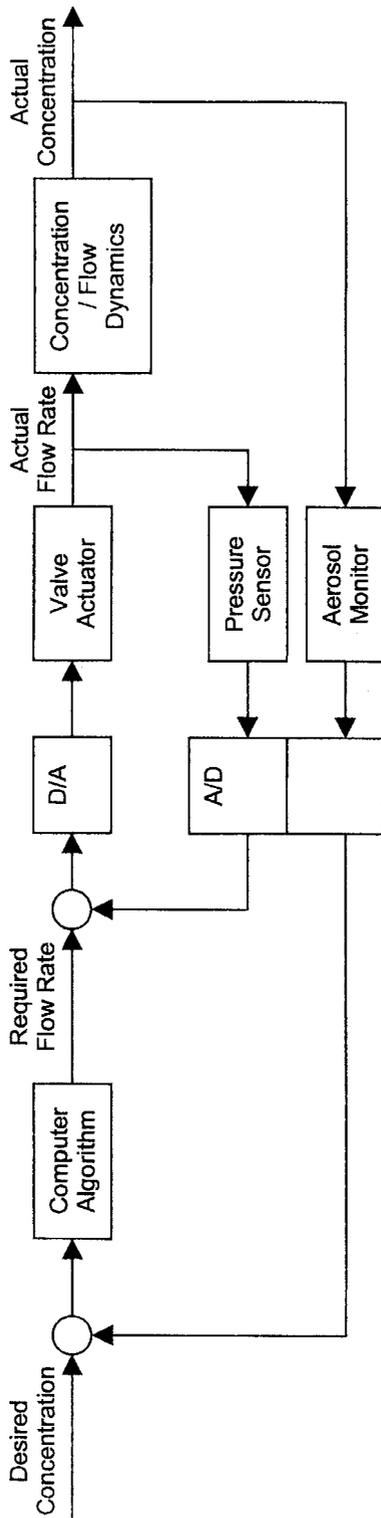
FIGURE 2. Block diagram of the automated feedback control system to control aerosol concentrations with changes in valve position.

the photometer was subsequently deposited on the filter. This "sample train" was placed in the middle of the second shelf during all trials, and facing into the direction of air flow across the shelf, after a separate analysis showed this location contained dust concentration levels that approached the mean level of the entire chamber (O'Shaughnessy, 1993). The average chamber concentration was therefore determined both by averaging all photometer readings for a particular trial and by gravimetric analysis of the backup filter. The ratio of monitor- to filter-derived measurements (M/F) was subsequently used as a measure of photometer accuracy. Previous research demonstrated that photometer accuracy was partially dependent on the standard deviation of the photometer readings over time, where larger fluctuations in successive readings diminished sensor accuracy (O'Shaughnessy & Hemenway, 1994). However, photometer readings were shown to be accurate to within ±10% of filter measurements under the largest concentration fluctuations recorded during those trials. The use of this device as a feedback control element was therefore determined to be justifiable given that level of accuracy.

As part of this research, the relationship between chamber flow rate and photometer response was determined by performing 180-min trials at flow rates of 0.1, 0.2, 0.3, 0.4, and 0.5 m^3/min. A chamber concentration near 10 mg/m^3 was maintained for all trials. During each trial, the M/F ratio was determined and an eight-stage cascade impactor (model 216-LA, Anderson Instruments, Smyrna, GA) was used to determine the aerosol size distribution obtained at each flow rate. Therefore, photometer response was first related to changes in size distribution then subsequently related to changes in flow rate. The resulting relationship between photometer response and flow rate was incorporated into a computer algorithm to automatically compensate photometer readings after a change in flow rate.

Affect of Flow on Aerosol Losses

A determination of the effect of flow rate on overall losses of aerosol in the chamber was made by comparing the actual concentration (C_A), measured gravimetrically, with the nominal concentration (C_N). The nominal concentration was first computed from a knowledge of the generator output rate, R_N (mg/min), and the chamber air flow rate, Q (m^3/min), where

$$C_N = \frac{R_N}{Q} \tag{1}$$

During this investigation, three 180-min trials were performed at flow rates of 0.1, 0.2, 0.3, 0.4, and 0.5 m^3/min while operating with a constant R_N. After each trial, C_A was compared with C_N to determine the fraction remaining, $F = C_A/C_N$, relative to flow rate.

Feedback Control

Computerized feedback control, utilizing a proportional-integral-derivative (PID) control algorithm (Sheble, 1999; VanDoren, 1996), was developed to automatically change flow rate based on photometer readings to maintain aerosol concentrations near a desired level. Often when applying feedback control, the response of the controlled system to a change in the input level results in some undesirable behavior, such as never reaching the desired steady-state level; sinusoidal oscillations prior to reaching the desired level; sudden "overshoot" of the controlled variable; or a lengthy time period to reach the new level. A PID algorithm, in essence, transforms the input signal to avoid these undesirable response characteristics by augmenting the signal proportionally (P); by integrating the signal to ensure the system will reach the desired level (I); and by making adjustments based on the derivative, or difference, in successive readings to dampen oscillations (D). A set of three constants, K_P, K_I, and K_D, one for each of the P, I, and D terms of the algorithm, respectively, can be chosen to obtain the desired response.

Prior to application of the PID algorithm to the actual system, a dynamic model of the process was first identified (O'Shaughnessy et al., 1996). This model consisted of a differential equation that related changes in flow rate with subsequent changes in concentration. Software capable of performing numerical simulations of feedback control systems (MATLAB, MathWorks Inc., Natick, MA) was then employed to simulate the response of the chamber system when employing the PID algorithm under varying sets of PID constants. A set of PID constants was chosen to produce a slow response with little overshoot. Three 180-min trials were then performed to test the performance of the PID control algorithm by first setting the flow rate to 0.3 m^3/min (the mid-range of available flow rates) and a fixed generator output rate required to produce a concentration near 10 mg/m^3. A similar set of 3 trials was also performed at a level of 25 mg/m^3 by increasing the generator output rate accordingly. Thirty minutes was allowed after initiating each trial to reach a relatively stable concentration followed by PID-controlled flow rates for 150 min for the 10-mg/m^3 trials and 50 min for the 25-mg/m^3 trials. A shorter trial time was required for the 25-mg/m^3 trials because packed dust in the generator was exhausted after that time span. Results from these trials were compared with a similar set of 3 trials at each level of 10 mg/m^3 and 25 mg/m^3 when operating at a constant generator output rate and dilution-air flow rate.

RESULTS

M/F Ratio Corrections

As shown in Figure 3, the aerosol size distribution shifted with a change in dilution-air flow rate. Mass median aerodynamic diameters (MMADs)
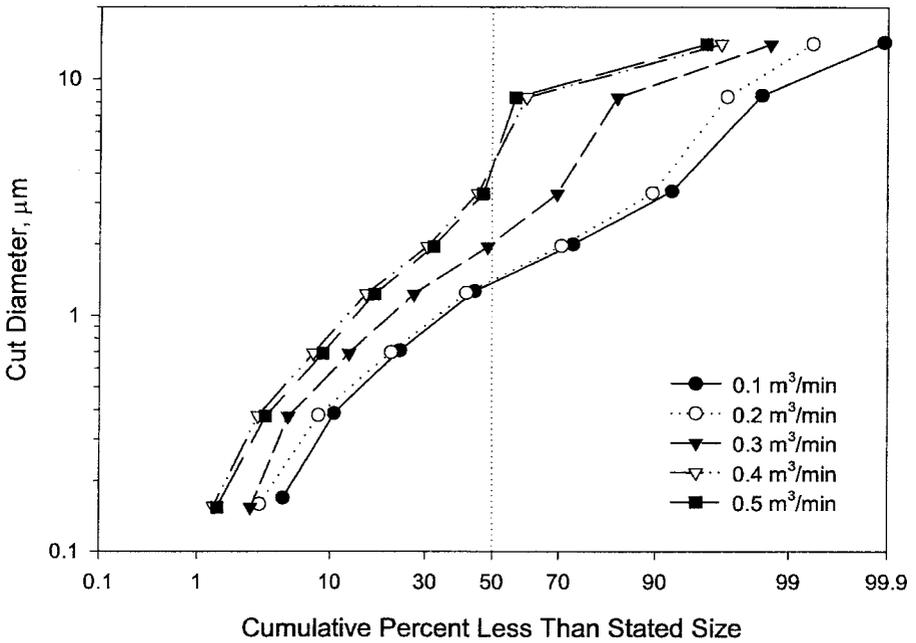
FIGURE 3. Aerosol size distributions resulting from changes in flow rate through the chamber.

ranged from 1.1 μm to 3.3 μm with a change in flow from 0.1 m³/min to 0.5 m³/min, respectively. Mass frequency plots of the resulting size distributions were made from data acquired when operating at the two flow rates mentioned earlier (Figure 4) (Hewett & McCawley, 1991). These plots indicate that the shift in MMAD was a consequence of reducing sedimentation time, which allowed large particles to remain airborne in the center of the chamber at the higher flow rates.

Results from the trials performed to establish the relationship between flow and the M/F ratio demonstrated a decrease in photometer response with an increase in flow rate and, hence, an increase in MMAD. As noted by Willeke and Baron (1990), this response pattern is common to all aerosol photometers. Furthermore, Smith et al. (1987) found that monitor response is best predicted by a linear function of 1/MMAD. Therefore regression analysis was performed to relate M/F to the inverse of MMAD (Figure 5). Furthermore, a nonlinear regression analysis of the relationship between flow rate and MMAD (Figure 6) demonstrated that the two variables were best characterized by a sigmoidal function of the form:

$$MMAD = A + \frac{B}{1 + \exp\left(-\dfrac{Q - S}{T}\right)} \tag{2}$$

where A indicates the minimum MMAD value; B is the interval between minimum and maximum MMAD; S represents the flow rate at the maximum slope; and T determines the maximum slope of the curve. Therefore, to compensate for a change in photometer response with a change in flow rate at each sample period, computer code was written to relate the change in MMAD with any change in Q that may have occurred with the use of the equation given in Figure 6. The code then included the equation given in Figure 5 to relate the calculated MMAD value with the M/F ratio. Finally, the photometer concentration value was corrected by dividing by the calculated estimate of M/F.
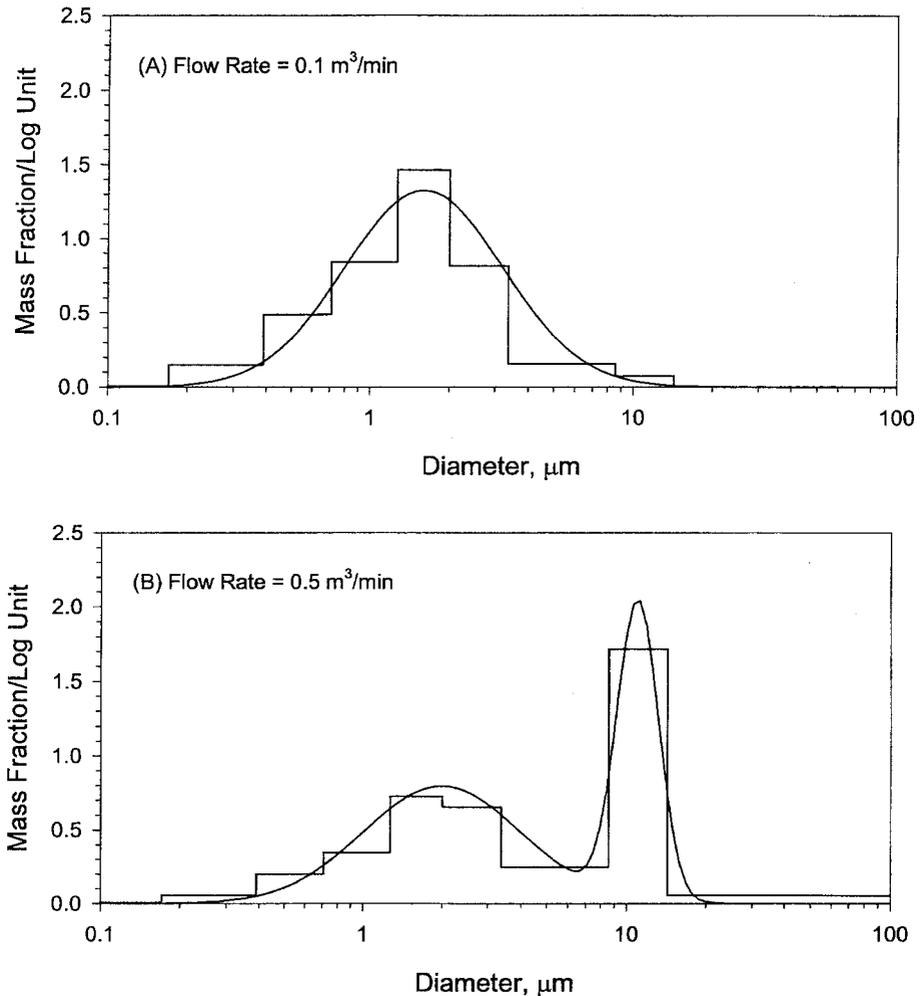

FIGURE 4. Shift in aerosol size distribution between lowest and highest air flow rates analyzed.
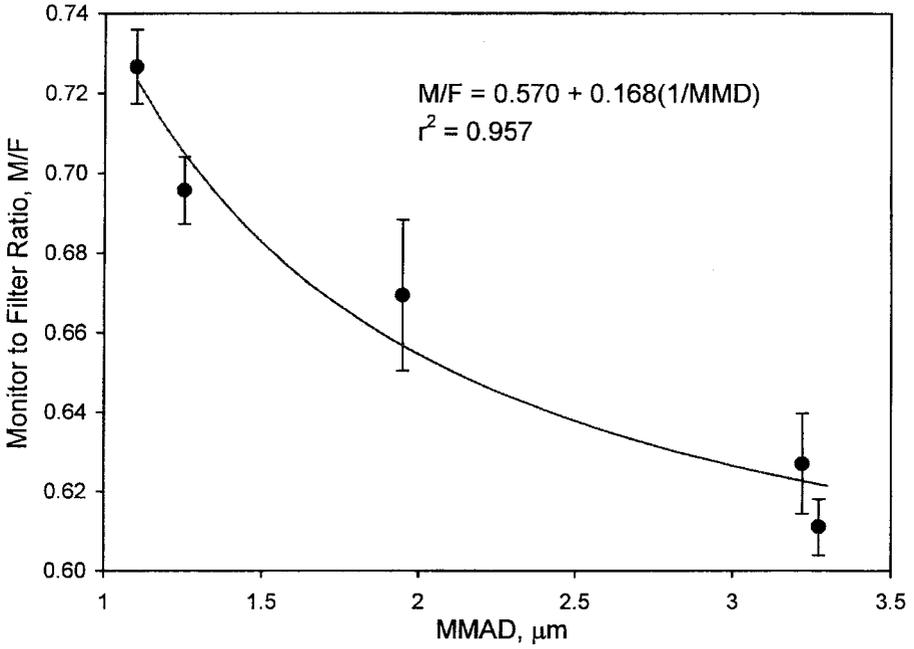
FIGURE 5. Monitor response ratio, standard deviations, and regression on median aerosol diameters.
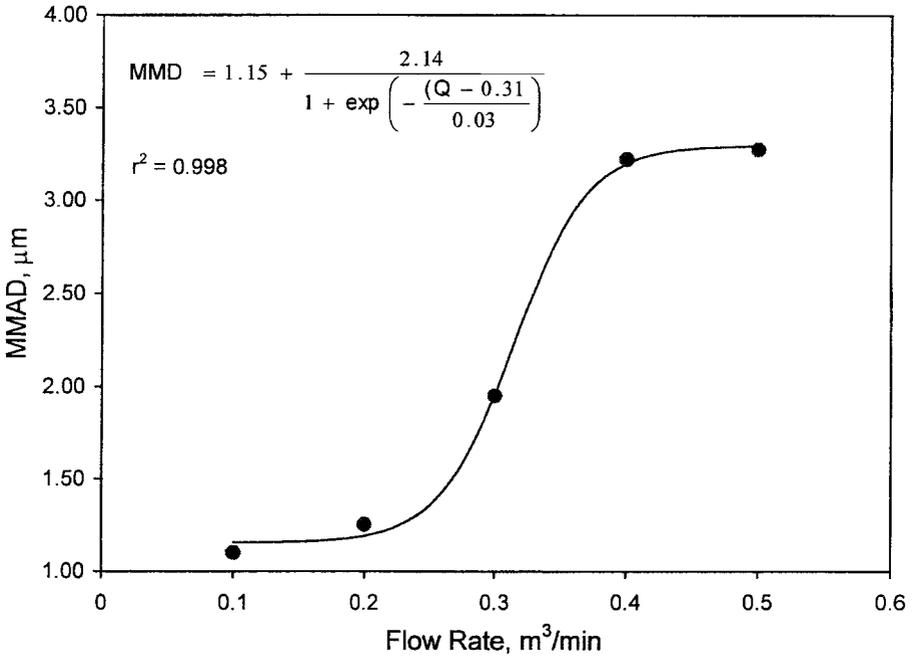

FIGURE 6. Regression relating median aerosol diameters to chamber air flow rate.

Flow Rate Corrections

As described earlier, the fraction remaining, F, is the ratio between the actual concentration, C_A, as measured by gravimetric analysis, and the nominal concentration, C_N, calculated from the mass output rate of the aerosol generator and the chamber flow rate. Under the assumption that particles were settling in a manner similar to that which occurs during horizontal elutriation, F is related to the inverse of Q (Hering, 1995). A linear regression was therefore made to relate F and $1/Q$ (Figure 7).

The relationship between Q and F given in Figure 7 had significant consequences when attempting to determine the proper flow rate for maintaining chamber concentrations near some desired level. Given the aerosol production rate, R_N, Q, and F, a desired concentration, C_D, can be calculated by:

$$C_D = \frac{R_N}{Q} F \qquad (3)$$

Therefore, the flow rate necessary to achieve a desired concentration is:
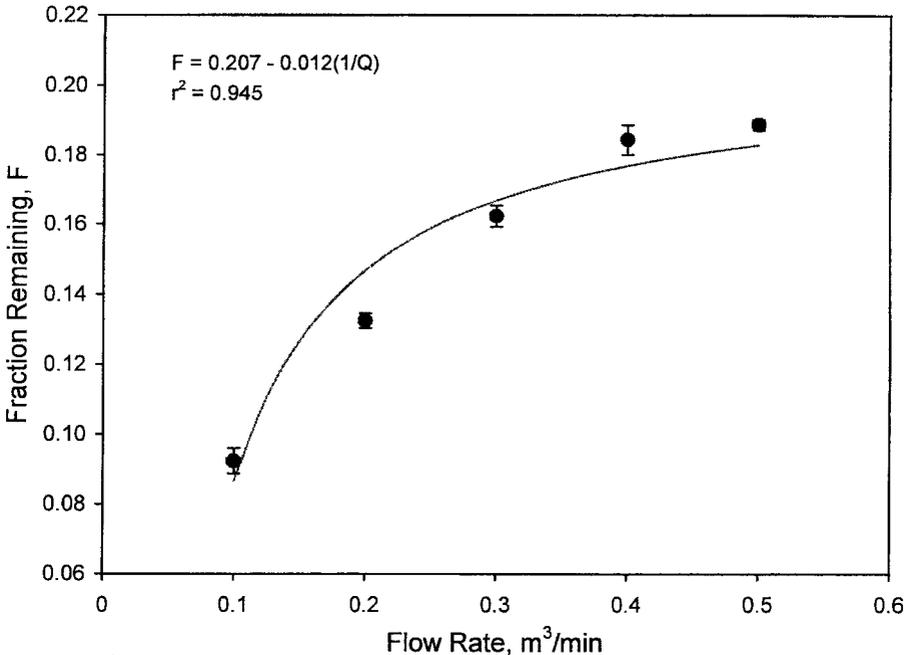
$$Q = \frac{R_N}{C_D} F \qquad (4)$$

$$F = 0.207 - 0.012(1/Q)$$
$$r^2 = 0.945$$

FIGURE 7. Fraction of generated dust remaining as an aerosol relative to chamber air flow rate.

However, F is a linear function of $1/Q$ of the form:

$$F = b + m(1/Q) \tag{5}$$

To relate the required flow rate needed to achieve a desired concentration, Eq. (4) and Eq. (5) were solved simultaneously, which resulted in the quadratic expression:

$$Q^2 C_D - QR_N b - R_N m = 0 \tag{6}$$

Therefore, the required Q could be determined by solving for the positive root of Eq. (6) with the use of the quadratic formula:

$$Q_C = \frac{R_N b + \sqrt{(R_N b)^2 + 4C_D R_N m}}{2C_D} \tag{7}$$

However, the use of Eq. (7) to predict flow rate was constrained when increasing concentration with reductions in flow rate. When increasing concentration beyond approximately 60% of the starting concentration, the quantity under the radical sign became negative and therefore impossible to calculate. Furthermore, a high flow rate could be calculated to achieve a very low desired concentration, but the maximum flow rate possible for the air mover in the system set a lower limit on possible reductions in concentration.

Automatic Feedback Control

The behavior of aerosol concentrations in the chamber during a portion of the system identification procedure is given in Figure 8. As described earlier, these data were used to determine a suitable dynamic model of the flow–concentration system. A simulation of the response produced by a feedback control system utilizing PID control and the identified dynamic model was performed to determine an appropriate set of PID constants. As shown in Figure 9, a change in the magnitude of the constants applied to the simulation resulted in different responses to a sudden change in input level. An original set of constants ($K_P = 0.9$, $K_I = 0.1$, and $K_D = 0.5$) was chosen that appeared to give a satisfactory response with only a slight amount of overshoot and smooth transition to a steady-state level. However, as shown in Figure 10A, application of these constants to the PID-controlled chamber ventilation rate resulted in the development of oscillations after inducing changes in the desired concentration. Therefore, a new set of constants ($K_P = 0.8$, $K_I = 0.08$, and $K_D = 0.1$) was chosen that, by simulation (Figure 9), would not produce overshoot. This change resulted in a satisfactory response that removed obvious oscillations (Figure 10B).

An example of typical concentration measurements resulting from a PID-controlled process is given in Figure 11. As shown in Table 1, the ratio
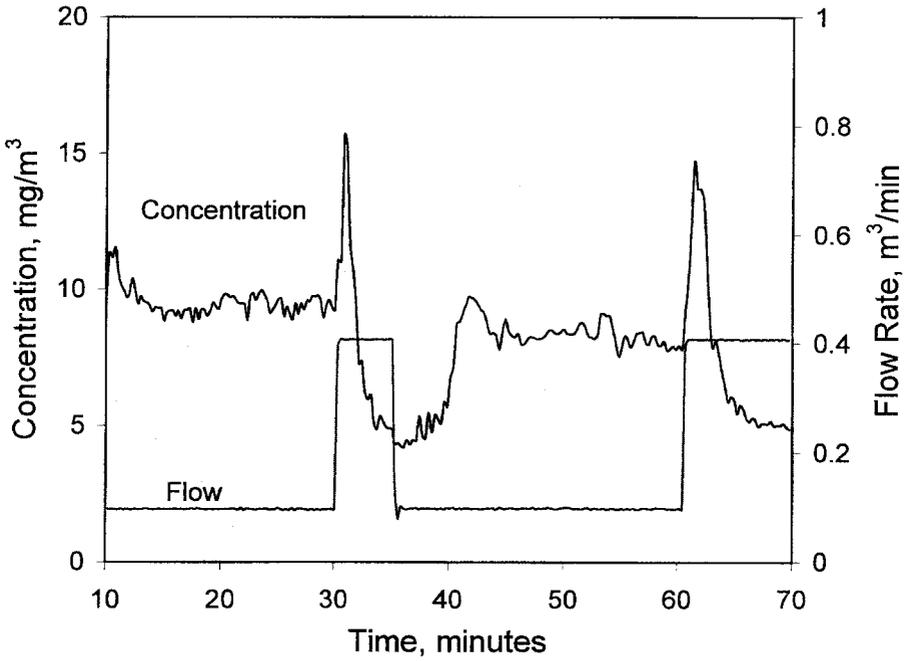
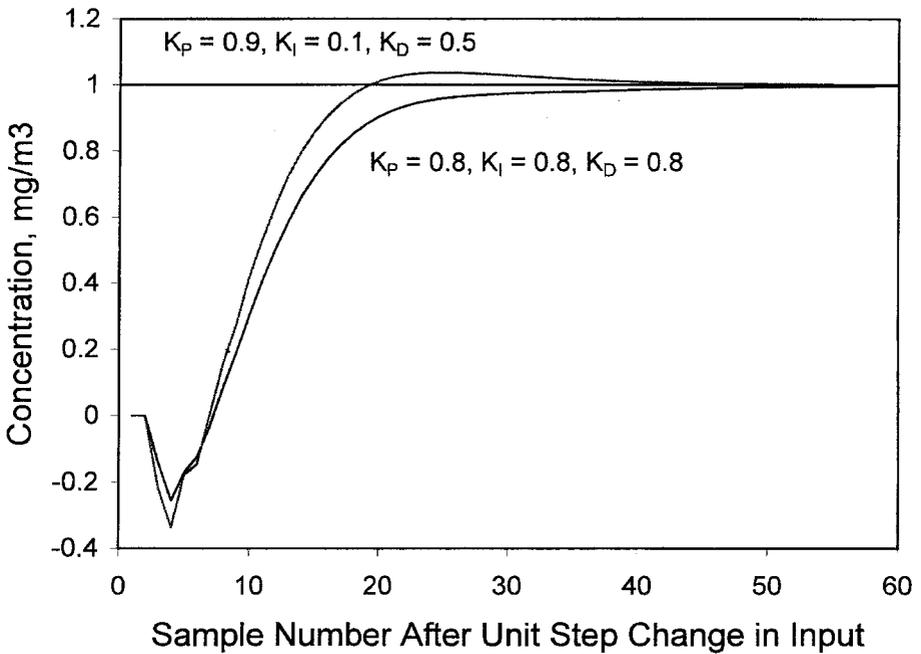**FIGURE 8.** Monitor readings and chamber flow rates when inducing sudden changes in flow rate.

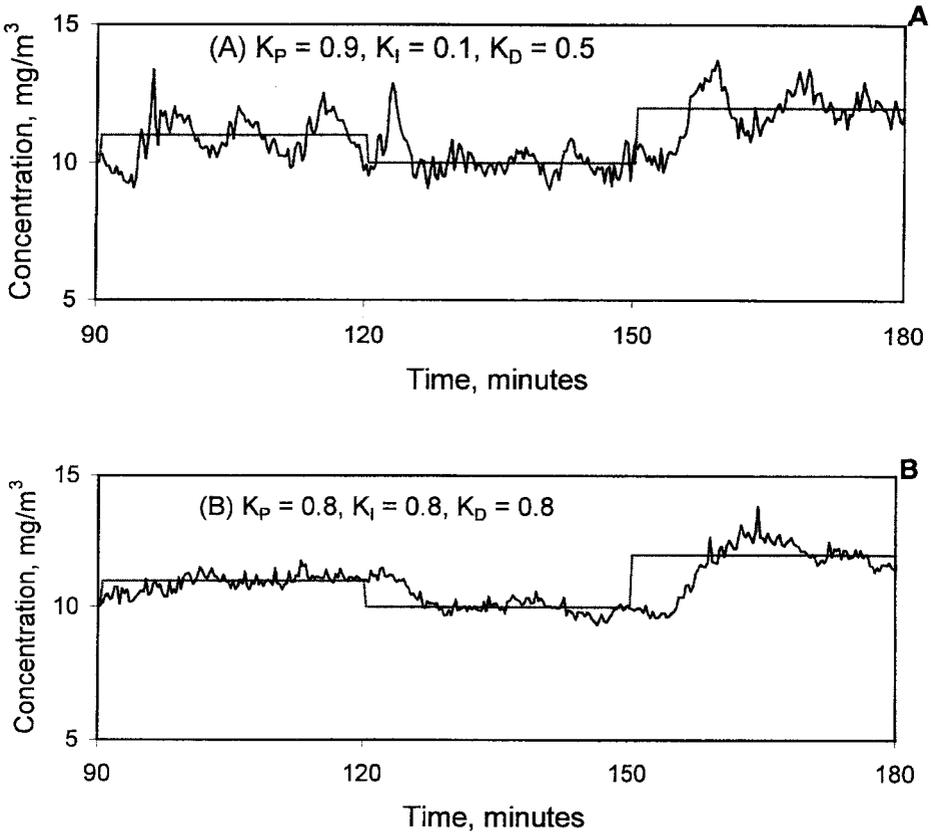**FIGURE 9.** Simulated system response with two sets of PID constants

FIGURE 10. Actual system response with PID constants causing an oscillating (A) and satisfactory (B) response.

of averaged monitor readings to the desired concentration level was near unity when employing feedback control. However, the standard deviations of measurements taken during comparable trials without feedback control were approximately one-half of those produced under feedback control (Table 1). As shown in Figure 11, relatively large fluctuations in flow rate were induced by the feedback system during some trials as a consequence of the system's response to similar fluctuations in the aerosol concentration. Despite the large fluctuations often evident in photometer readings, the M/F ratios calculated for each trial were close to unity and statistically similar to M/F ratios produced during the steady-flow, uncontrolled trials ($p = .65$) (Table 1).

DISCUSSION

A typical goal associated with the production of an aerosol for inhalation toxicology research is to maintain that concentration consistently near a desired level. An aerosol photometer placed inside the exposure
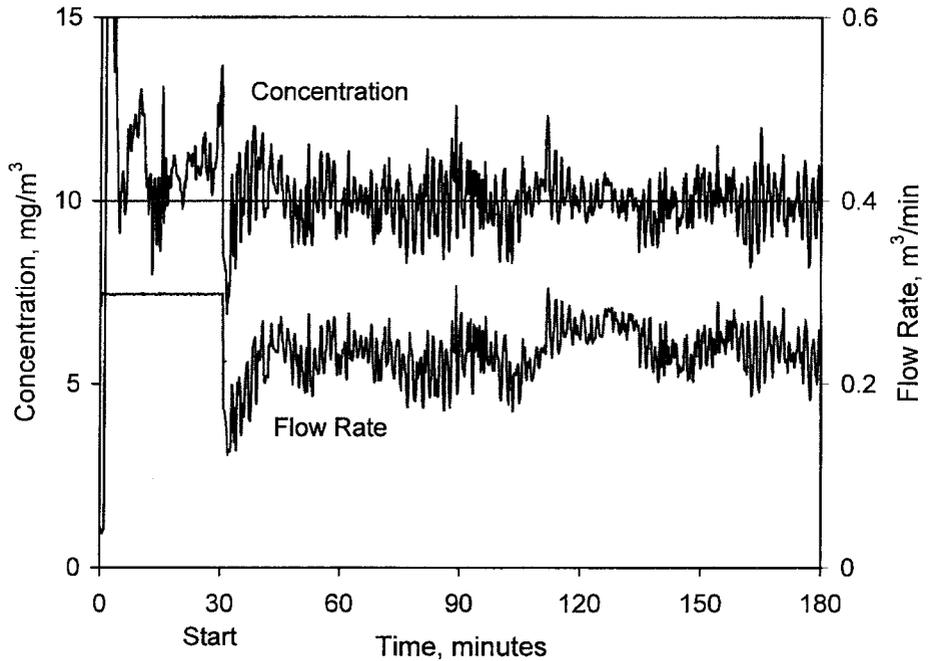
FIGURE 11. Monitor readings and chamber flow rates under PID feedback control to maintain concentrations near 10 mg/m^{3}.

chamber allows an operator the ability to make adjustments to chamber flow rate and/or generator output rate to correct for deviations in concentration from the desired level. Implementation of a computerized feedback control system can then allow for automatic changes to the controlled variable. The accuracy of such a system is then related to (1) the ability of the photometer to correctly indicate chamber concentration levels

TABLE 1. Comparison of uncontrolled and PID-controlled trials (average ± standard deviation)

	Uncontrolled trials		PID-controlled trials	
	10 mg/m^{3} Trials	25 mg/m^{3} Trials	10 mg/m^{3} Trials	25 mg/m^{3} Trials
Ratio of monitor average to desired level[a]	1.003 ± 0.045	0.880 ± 0.045	1.002 ± 0.006	0.997 ± 0.005
Measurement standard deviation	0.454 ± 0.215	1.136 ± 0.609	1.064 ± 0.237	2.212 ± 0.609
M/F ratio	1.036 ± 0.006	0.948 ± 0.018	1.013 ± 0.186	0.965 ± 0.013

[a]Average of all monitor readings during uncontrolled trials. Average only of readings taken during period of PID control during PID-controlled trials.

and (2) the calculation of an adjustment of appropriate magnitude to correct for a deviation between actual and desired concentrations.

Photometer response was found to vary with changes in flow due to a corresponding shift in the particle size distribution. Therefore, to maximize the accuracy of the sensor under varying dilution-air flow rates, the nonlinear relationship between flow rate and monitor response was incorporated into the computer algorithm controlling flow rate. Furthermore, the amount of dust remaining as an aerosol also changed with flow rate. As expected, losses increased with a decrease in flow rate due to the increased time allowed for particle settling, as well as particle-to-wall deposition, prior to reaching the center of the chamber at lower flows. This condition implied that a simple inverse relationship between concentration and the necessary flow rate required for contaminant dilution was inadequate and a more complicated equation was required to relate the two variables.

Because a particular inhalation chamber and aerosol type were used during these studies, the results given in the table and figures are only directly applicable to that chamber and aerosol. However, these results demonstrate a behavior of both aerosol photometers and aerosols in inhalation chambers that can be considered typical regardless of the photometer used or dust type generated. Changes in flow rate through a chamber will necessarily affect the physical forces applied to the aerosol and lead to changes in the amount of aerosol lost by impaction and sedimentation and therefore a shift in the size distribution as well. Furthermore, it is a well-established fact that photometer response changes with a change in size distribution. Therefore, some compensation for a change in response, and hence photometer accuracy, is necessary. The degree to which aerosol losses and size-distribution shifts occur, as a consequence of changes in flow rate, must be determined for each chamber system and dust type generated. The general equations given earlier can then be applied and solved for each individual case. When applied in unison, these equations will compensate for aerosol losses when determining the appropriate flow rate needed to obtain a desired concentration level as well as compensate for changes in photometer response.

The control system investigated as part of this research involved the automatic adjustment of dilution-air flow rate to augment deviations in chamber concentration from a desired level. The PID feedback control method was chosen for analysis because it is a well-known and commonly used feedback control method. As demonstrated earlier, software capable of identifying a system's dynamic model and simulating the reaction of that model under feedback control can aid in the determination of appropriate PID tuning constants. However, random fluctuations, induced as a consequence of the system's reaction to random changes in concentration, were still evident in some trials despite efforts to choose and verify a set of constants that minimized those fluctuations.

Future work will involve the application of more sophisticated control methods such as the linear quadratic regulator (LQR) (Astrom & Wittenmark, 1984). The LQR was designed to optimally control a process by simultaneously (1) reducing the difference between actual concentration and the desired level and (2) constraining the fluctuations in valve movement and, hence, fluctuations in flow rate. Furthermore, as shown in Figure 8, a large increase in flow rate ultimately reduced the concentration, as expected, but an initial spike in concentration was produced immediately after the change. Evidently, the sudden increase in flow rate reentrained settled dust in the upstream side of the chamber. A spike in concentration of this sort will generally not occur when operating under feedback control, especially when PID tuning constants have been chosen to produce a "damped" (slow-rising) response. An undesirable increase in concentration of this type is also a consequence of the sampling period. During this research, a sampling time of 15 s was chosen relative to an average residence time of 3.3 min. Longer sampling intervals will allow a greater potential difference between actual and desired concentration to occur before a corrective action is taken. Therefore, the magnitude of compensating adjustments in flow rate will increase with an increase in sample interval, resulting in the potential for inducing concentration spikes.

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