

Using swine dust to verify a lumped-parameter model in a ventilated enclosure

W. GAO and J.J.R. FEDDES

Department of Forest Science, University of Alberta, Edmonton, AB, Canada T6G 2H1. Received 25 March 1992; accepted 21 January 1993.

Gao, W. and Feddes, J.J.R. 1993. Using swine dust to verify a lumped-parameter model in a ventilated enclosure. *Can. Agric. Eng.* 35:067-073. Swine dust was used as a test dust to verify a lumped-parameter model derived for predicting airborne dust concentrations at any location within a ventilated airspace. Average equilibrium airborne dust concentrations were predicted as a function of ventilation and dust generation rates. Time-dependent airborne dust concentrations at a designated location (or control volume), also were predicted from ventilation and dust generation rates. The model calculation, solved as a 3-D lumped form of control volumes, represented conservation of air mass flow rate. Swine dust used in this project had an average aerodynamic diameter of 2 μm and 95% of the dust particles were less than 5 μm in diameter and approximately 45% of the particles were 2 μm in diameter. Both ventilation rate and dust generation rate have a significant effect on airborne dust concentration. The lumped-parameter model is shown to be capable of predicting the ventilation rate required to maintain acceptable levels of airborne dust in confinement animal buildings. The accuracy of the model is influenced by the test dust particle size uniformity.

De la poussière de porcherie a été utilisée pour valider un modèle de prédiction tridimensionnel des concentrations de poussière en suspension aérienne dans un espace ventilé. Les concentrations moyennes de poussière en suspension furent prédites en fonction des taux de ventilation et de propulsion aérienne de la poussière. Les variations des concentrations de poussière en suspension en fonction du temps furent aussi prédites pour certaines zones désignées de l'espace tridimensionnel de contrôle. Les calculs du modèle sont basés sur la conservation de masse entre les différentes zones. La poussière de porcherie utilisée pour ce projet avait un diamètre aérodynamique de 2 μm et 95% de la poussière avait un diamètre inférieur à 5 μm alors que 45% de particules était de 2 μm en diamètre. Les taux de ventilation et de propulsion de poussière ont eu un effet significatif sur les concentrations de poussière en suspension aérienne. Ce modèle de prédiction tridimensionnel des concentrations des poussières est capable de prédire le taux de ventilation requis pour maintenir des niveaux acceptables de poussière en suspension aérienne dans les bâtiment d'élevage. La précision du modèle dépend de l'uniformité de la taille des particules de poussière.

INTRODUCTION

Dust is one of the main aerial contaminants in swine confinement buildings and results from animal activity, air movement, finely ground dry feed introduced during feeding, and fecal-feed particles deposited on a solid floor and later entrained into the air. Although dust particles tend to settle

out, they can be continuously reintroduced into the airspace. The behavior of aerosols in a ventilated airspace is of fundamental and practical significance because it not only provides useful information for the simulation of aerosol processes, but also provides information useful in the design of removal mechanisms.

Although some models have been developed to predict aerosol concentration distribution in livestock buildings, no attempt has been made to validate the predicted distribution using swine dust particles.

A general model was developed to understand the phenomenon of airborne dust transport from the viewpoint of a lumped-parameter approximation for describing the dynamics of airborne dust at any location within a ventilated airspace (Liao and Feddes 1990a). An experiment was carried out in an environmental chamber to assess the accuracy of the model using talcum powder as a test dust (Liao and Feddes 1990b). The predictions of the model compared very favorably with the measured results. Talcum particles have an average aerodynamic diameter of 1 μm and their particle size distribution is quite uniform (Liao and Feddes 1990b). The objective of this study was to compare the results of dust concentrations obtained by the lumped-parameter model calculation and by measurement using dust collected from a swine barn. Both ventilation rate and dust generation rate were varied to test their effect on airborne dust concentration.

EXPERIMENTAL FACILITIES AND PROCEDURES

The experiment was carried out in the environmental chamber used by Liao and Feddes (1990b) (Fig. 1). The dust used throughout the experiment was collected from an occupied pen floor in a feeder swine barn. The collected dust was sieved through a screen with 4.76 mm openings to separate the larger material. To obtain a homogeneous and finer dust, the screened dust was mixed in a rolling cylinder for one hour.

Dust generation system

The dust was placed in a hopper and transported by an auger to a blower that injected it into the ventilated airspace via six dust generation locations (Fig. 2). The dust generating points were 270 mm above the floor. The generation rate was changed by installing augers with different pitches.

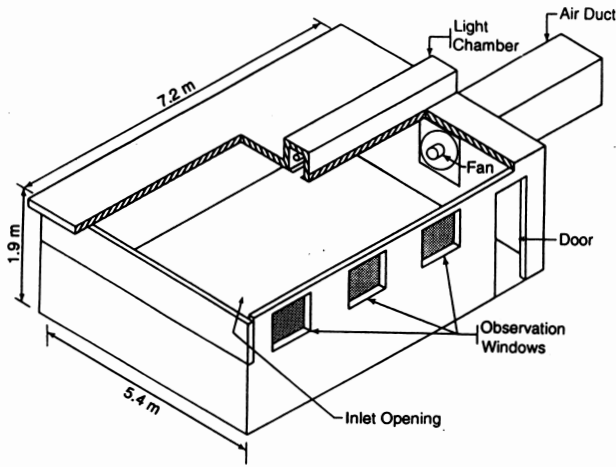


Fig. 1. Overall view of large-size environmental chamber (Leonard 1986).

Dust sampling and analyzing system

An Aerodynamic Particle Sizer System (TSI, St. Paul, MN) was used to measure dust particle concentration. Before the test, the unit was calibrated with particles of latex microspheres polystyrene (0.496, 0.966, 2.01 μm), Polymer Microspheres Styrene-Vinyltoluene Latex (2.96 μm), and Polymer Microspheres (3.983, 9.870 μm) (Duck Scientific Corp., Palo Alto, CA).

Dust concentration was monitored at each sampling point in each of the control volumes (Fig. 3). Before each trial run, the environmental chamber was thoroughly cleaned with a vacuum cleaner. Airflow rates and dust particle concentrations from each of the six dust generation points were measured prior to each experiment. These data were used to calculate dust generation rates. Dust samples from each control volume were drawn to the particle sizer via a 13 mm ID, 4 m long Tygon plastic tubing. Dust particle velocity was sufficient to prevent particles from settling inside the sampling tubes although the tubes were routinely cleaned using compressed air before each sampling period. The sampling point in control volume 5 was used to study the transient airborne dust concentration by sampling at 2-min intervals. After 100 min, concentrations at the 12 sampling points were measured in random order at 2-min intervals repeated twice.

Ventilation system

Air entered the experimental chamber from an air-condi-

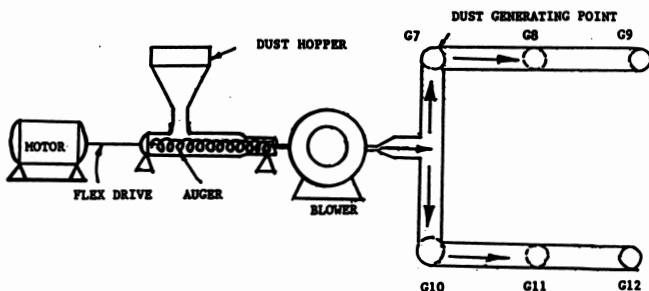


Fig. 2. General outline of dust generating system.

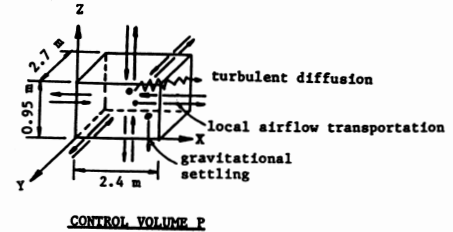
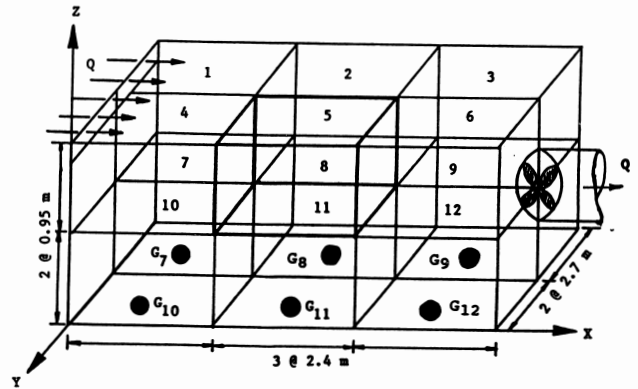


Fig. 3. Twelve lumps and a control volume P used in the model verification.

tioned laboratory through an inlet (5.40 m x 45 mm) (Fig. 1). A 640-mm propeller exhaust fan was operated by a controller to maintain constant ventilation airflow rates over the sampling period. The airflow rate was measured in a discharge duct by a hotwire anemometer in accordance with Jorgenson (1983). Three ventilation rates were chosen to simulate both cold and warm weather conditions. The inlet was adjusted to maintain a 15 Pa negative pressure.

Airflow patterns were identified in the chamber by using smoke pencils. The smoke distribution became uniform in the chamber after 5 min (Liao and Feddes 1990b).

Experimental design

The primary dependent variable studied in this project was airborne dust concentration. Independent factors consisted of ventilation rates (0.083, 0.25, 0.416 $\text{m}^3 \cdot \text{s}^{-1}$) and dust generation rates (8.9 x 10⁶, 9.2 x 10⁶, 11.1 x 10⁶ particles $\cdot \text{s}^{-1}$). The two independent factors, each having three levels, were replicated three times in random order (Table I). These were arranged in a split-split-plot factorial experimental design so that the dust concentration data could be analyzed using an analysis of variance procedure.

PREDICTION OF DUST CONCENTRATION

The lumped-parameter model developed by Liao and Feddes (1990a) can be represented by a first-order vector-matrix differential equation:

$$d\{n(t)\}/dt = -[B]\{n(t)\} + [V]^{-1}\{G(t)\}, \quad n(0) = n_0 \quad (1)$$

where:

- {n(t)} = vector of dust particle concentration (particles $\cdot \text{m}^{-3}$),
- [V]⁻¹ = inverse diagonal matrix of air volume (m^{-3}),

Table I. The experimental design

Dust generation rate g (particles / s)	Ventilation rates (m ³ /s)		
	V ₁ (0.083)	V ₂ (0.25)	V ₃ (0.416)
g ₁ (low, 8.9x10 ⁶)	g ₁ V ₁	g ₂ V ₂	g ₁ V ₃
g ₂ (medium, 9.2x10 ⁶)	g ₂ V ₁	g ₂ V ₂	g ₂ V ₃
g ₃ (high, 11.1x10 ⁶)	g ₃ V ₁	g ₃ V ₂	g ₃ V ₃

{G(t)} = vector of time-dependent dust generation rate (particles•s⁻¹),
 [B] = square transport matrix (s⁻¹), and
 {n₀} = vector of initial airborne dust concentration (particles•m⁻³).

The equilibrium dust particle concentrations attained can be given as:

$$\{n(s, s)\} = [B]^{-1} [V]^{-1} \{G(s, s)\} \quad (2)$$

where:

{G(s,s)} = vector of equilibrium dust generation rate (particles•s⁻¹).

As shown in Fig. 3, the environmental chamber was divided into 12 control volumes. The control volume P in Fig. 3 is a representative volume in which dust particles are undergoing turbulent diffusive deposition and coagulation, gravitational sedimentation, and local airflow transport. The primary airflow and circulating airflow are assumed to be directed in the x, y, and z directions (Liao and Feddes 1990a).

To predict dust concentration by the model in each control volume, the following input data are required:

- a) The diagonal air volume matrix [V]: V₁ = V₂ = V₁₂ = 6.16 m³.
- b) Dust generation rate in control volumes 7, 8, 9, 10, 11, and 12 (Fig. 3).
- c) The transport matrix [B]: The input data to the transport matrix for each ventilation rate are according to the following equations:

$$[B] = [H]^{-1} + [V]^{-1} [S] + [V]^{-1} [Q] \quad (3)$$

where:

$$[H]^{-1} = [V]^{-1} [A]$$

$$[H]^{-1} = U_s(r) [H]^{-1}$$

$$[S] = ((D(R) + \epsilon) / \delta) [S]$$

in which:

[A] = diagonal matrix of control volume's cross-section area (m²),

[H] = diagonal matrix of control volume's height (m),

[S] = diagonal matrix of control volume's surface area (m²),

U_s(r) = particle terminal settling velocity (1.3x10⁻⁴ m•s⁻¹, Hinds 1982),

D(r) + ε = effective turbulent diffusion coefficient (3.34x10⁻⁷ m²•s⁻¹, Davies 1966), and

δ = thickness of concentration boundary layer (8.5x10⁻⁴ m, Van de Vate 1972).

d) The air flow matrix [Q]: [Q] is a square airflow matrix with entries Q_{ij} (j=source, i=destination),

where:

$$Q_{ij} = \begin{cases} -Q_{ij} & \text{for } i \neq j \\ \sum_{\substack{i=1 \\ (i \neq k)}}^m Q_{ki} & \text{for } i = j \end{cases} \quad (4)$$

The airflow matrix [Q] also can be expressed as:

$$[Q] = Q[\beta] \quad (5)$$

where:

[β] = square matrix of entrainment ratio function, and

Q = total volumetric flow rate of outdoor air supplied to the whole system (m³•s⁻¹).

By calculation, β = 6.76 at X = 7.2 (Liao and Feddes 1990b).

The input data of the airflow matrix are calculated using Eqs. 4 and 5 based on the airflow patterns which are shown schematically in Fig. 4.

An average particle aerodynamic diameter of 2 μm was used in the model calculation.

RESULTS

Size distribution of the test dust

Although this experiment did not focus on swine dust particle size distributions, dust concentration data did include these. Particle size analysis showed the swine dust used in this project had an average particle aerodynamic diameter of 2 μm; 95 percent of the dust particle sizes were less than the

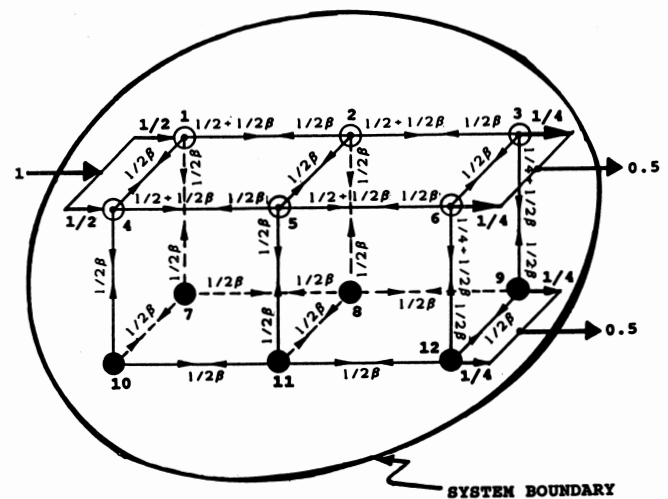


Fig. 4. Airflow patterns of a 12-lump model used in model verification.

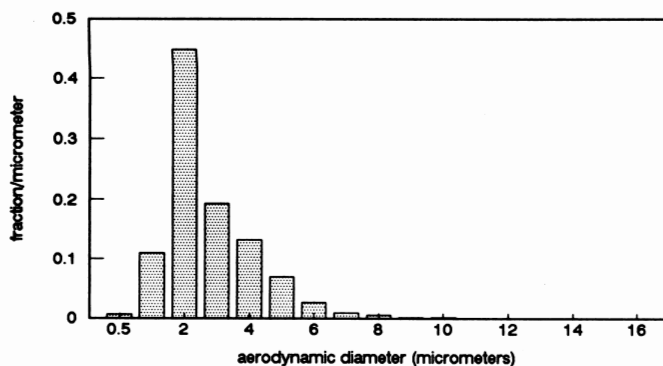


Fig. 5. Size distribution of the test swine dust.

respirable range (5 μm) while approximately 45 percent of the particles were in the range of 1.16 to 2.05 μm (Fig. 5).

Comparison of the measured with the predicted dust concentrations

To compare the measured and the predicted dust concentration, the test chamber was divided into two parts from the view point of height-from-floor level. Control volumes 1, 2, 3, 4, 5 and 6, are included in the upper level and the remainder in the lower level (Fig. 3). The average dust concentration of each level and the dust concentration differences between the two levels at different ventilation and dust generation rates are listed in Table II.

Table II indicates that at the upper level the measured dust concentrations are generally higher than those predicted except at the lowest ventilation rate, whereas, the measured values were greater than those predicted at the lower level. Average dust concentration difference between the two levels varied with ventilation rate. At high ventilation rates, the mean dust concentration difference between the two levels was very similar between predicted and measured values, while a greater discrepancy occurred at the low and medium ventilation rates. This discrepancy increased with increased dust generation rate.

The measured and calculated mean equilibrium airborne dust concentrations at the 12 sampling points for different ventilation rates and dust generation rates are shown in Fig. 6 to illustrate the trends. Minimum differences occurred between the measured values and those predicted by the model for the high ventilation rate. The greatest deviation (71.4%) from the predicted values occurred at medium ventilation rate. Total airborne dust concentration decreased as ventilation rate increased.

Figure 7 shows the comparison of the model predicted transient airborne dust concentration at control volume 5 with those measured for high and low ventilation rates with low dust generation rate. These figures indicated that fluctuations in measured airborne dust concentration in control volume 5 were much higher than those predicted by the model. At the low ventilation rate, measured concentrations were lower than that simulated; however, they were higher than those predicted at the high ventilation rate.

Table III indicates that as the ventilation rate increases, the measured and predicted airborne dust concentration de-

Table II. Comparison of the average dust concentration of the upper level lumps with that of the lower level lumps at three dust generation rates

Ventilation rate (m^3/s)	Average equilibrium dust concentration (10^6 particles)			
	Upper level		Lower level	
	pred ¹	meas ²	pred	meas
	low			
0.083	66.9 (2.4) ³	62.7 (25.2)	71.0 (1.3)	166.0 (102.8)
0.250	28.9 (1.1)	78.3 (51.9)	30.5 (0.5)	126.8 (62.6)
0.416	18.4 (0.7)	42.8 (19.3)	19.4 (0.3)	44.4 (21.0)
	medium			
0.083	69.0 (2.8)	83.3 (52.6)	73.4 (1.5)	213.8 (94.5)
0.250	29.9 (1.2)	77.5 (33.0)	31.5 (0.6)	132.0 (48.9)
0.416	19.0 (0.8)	46.3 (14.8)	20.0 (0.4)	45.4 (16.8)
	high			
0.083	83.5 (2.8)	76.8 (39.6)	88.7 (1.8)	314.2 (77.6)
0.250	36.1 (1.3)	106.8 (54.6)	38.1 (0.3)	215.4 (98.8)
0.416	23.0 (0.9)	70.5 (25.7)	24.3 (0.2)	70.0 (31.9)

¹ Predicted values (average particle aerodynamic diameter = 2 μm)

² Measured values (mean of the three replicates)

³ Standard deviation (n = 12)

crease. Theoretically, airborne dust concentrations should decrease by 57% when the ventilation rate is increased by a factor of 3 (0.083 $\text{m}^3 \cdot \text{s}^{-1}$ to 0.25 $\text{m}^3 \cdot \text{s}^{-1}$). However, actual airborne dust concentration only decreased an average of 20% for the three dust generation rates. When ventilation rate approached 0.25 $\text{m}^3 \cdot \text{s}^{-1}$, the measured dust concentration decay rate (56%) was higher than that predicted by the model (36%).

An analysis of variance indicated that the overall differences in particle concentration due to ventilation rate, dust generation rates were significant. However, the interaction

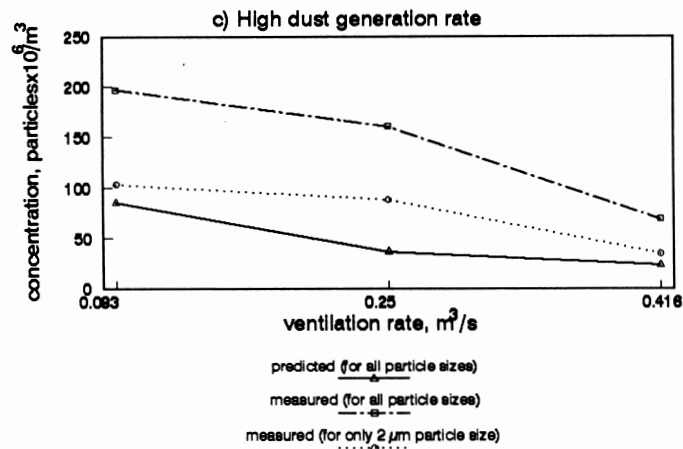
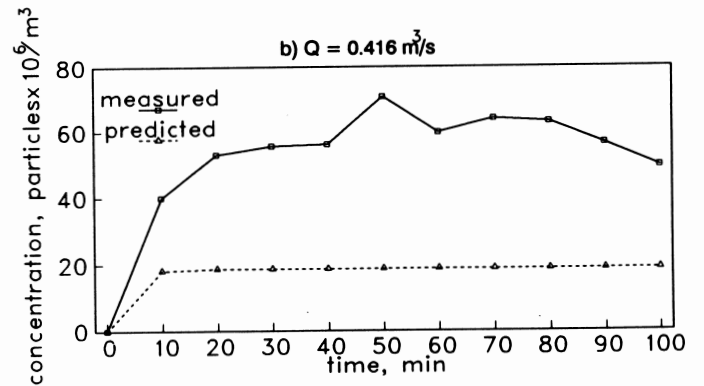
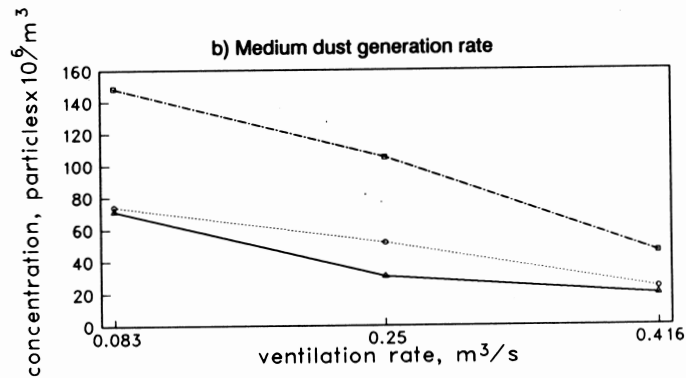
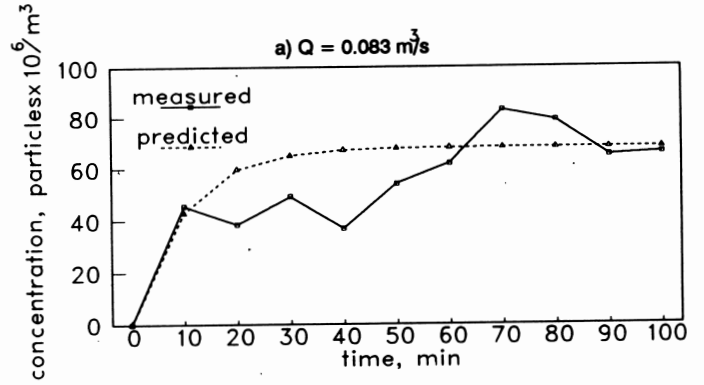
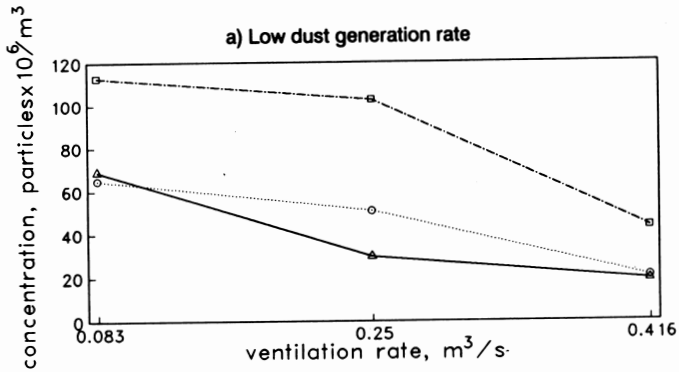


Fig. 7. The transient behavior of the predicted airborne dust concentration and that measured in control volume 5 at the low dust generation rate.

Table III. Effect of ventilation rate increase on measured and predicted dust concentration

Ventilation rate (m ³ /s)		Airborne dust concentration decrease in the environmental chamber (%)					
		g ₁ ¹		g ₂		g ₃	
from	to	meas ²	pred ³	meas	pred	meas	pred
0.083	0.250	11.9	56.9	30.6	56.9	17.6	56.9
0.083	0.416	62.8	72.4	69.1	72.6	64.0	72.6
0.250	0.416	57.7	36.4	55.5	36.4	56.4	36.4

1 Dust generation rate: g₁ = low, g₂ = medium, g₃ = high
 2 Measured dust concentrations
 3 Predicted dust concentrations

Fig. 6. Comparison of average equilibrium dust particle concentrations to those predicted for different ventilation rates.

between ventilation rate and dust generation rate was not significant.

DISCUSSION

From the dust concentration results, the most significant sources for the discrepancies occurring between the experimental and the predicted results were considered to be the following:

1. Dust particle size uniformity: Most aerosol properties depend strongly on particle size and this variable is best controlled by using monodisperse aerosols (Hinds 1982). This is supported by the good agreement occurring between the measured values and those calculated in the talcum powder experiment (Liao and Feddes 1990b) since talcum particles are much more uniform in size than swine dust particles. It is interesting to note that if only the mean particle size of $2\ \mu\text{m}$ was considered as measured airborne dust concentration in the experimental chamber, the differences between the measured and those predicted by the model decreased dramatically (Figure 6).
2. Homogeneous mixing: Actual conditions may significantly depart from homogeneous mixing that is assumed in deriving the system equation (Liao and Feddes 1990a). In developing the linear dynamic equation, the entrainment ratio and the airflow patterns are assumed to be the same for the three different ventilation rates used. However, the actual airflow entrainment and the airflow patterns will likely change with ventilation rates (Barber and Ogilvie 1982). The airborne dust concentration difference between the upper level control volumes and the lower level control volumes (Table II) indicate that the mixing is affected by the ventilation rate. The disagreement between the predicted and the measured dust transient behavior illustrated in Fig. 7 appears to show the departure from the assumptions made. Furthermore, if temperature gradients are established in the ventilation flow field because of recirculating of cool air, a thermophoresis effect will disturb dust sampling readings (Hinds 1982). The error caused by departure from homogeneous mixing that is assumed in deriving the system equation can be reduced by increasing sampling points in a given space.
3. The airflow matrix $[Q]$: Because of the inherent limitations in predicting airflow within a ventilated airspace, the assumptions of the behavior of the local transport mechanisms made in each control volume may depart from the actual situation and cause the system equation to underestimate dust concentration; especially, the dust concentrations of the lower level control volumes at low and medium ventilation rates. A similar situation occurred when talcum powder was used as a test dust (Liao and Feddes 1990b).
4. Low ventilation rates: Instability of the airflow patterns within a building may occur at low ventilation rates (Randall 1980) therefore leading to greater discrepancy between the predicted and the measured values and higher dust concentration fluctuations.

SUMMARY AND CONCLUSIONS

The purpose of this project was to verify the lumped-parameter model for predicting airborne dust concentrations in a ventilated airspace using a swine test dust and to test the hypothesis that dust generation and ventilation rates do not affect airborne dust concentration. Conclusions drawn from this study were as follows:

1. The lumped-parameter model is capable of predicting the rate of ventilation required to maintain acceptable levels of airborne dust in confinement animal buildings on dust generation rate when the mean particle size is entered into the model.
2. Significant differences occurred between airborne dust concentrations for the ventilation and dust generation rates used. The interaction of ventilation rate and dust generation rate on dust concentration was not significant.
3. Levels of airborne dust change with height from the floor levels and are affected by ventilation rate. The actual airborne dust concentration differences between the upper and lower level lumps are significantly different from those predicted by the model at low and medium ventilation rates.
4. When ventilation rate was increased from $0.083\ \text{m}^3\cdot\text{s}^{-1}$ to $0.25\ \text{m}^3\cdot\text{s}^{-1}$, the measured airborne dust concentration dilution rate (20%) was lower than that predicted (57%). The measured dust concentration decreased by 56% when ventilation rate increased from $0.25\ \text{m}^3\cdot\text{s}^{-1}$ to $0.416\ \text{m}^3\cdot\text{s}^{-1}$; however, the predicted dust concentration decrease was 36%.
5. The discrepancy between measured and calculated results decreased when the measured dust concentration only consisted of $2\ \mu\text{m}$ particles. The discrepancy ranged from a minimum of 3.9% to a maximum of 58%.
6. Swine dust used in this experimental study had an average aerodynamic diameter of $2\ \mu\text{m}$, 95% dust particles were less than $5\ \mu\text{m}$ in size while approximately 45% of the particles were $2\ \mu\text{m}$ in diameter.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Science and Engineering Research Council of Canada and the Alberta Agricultural Research Institute.

REFERENCES

- Barber, E.M. and J.R. Ogilvie. 1982. Incomplete mixing in ventilated airspace. Part I. Theoretical consideration. *Canadian Agricultural Engineering* 24:25-29.
- Davies, C.N. 1966. Deposition from moving aerosols. In *Aerosol Science*, ed. C.N. Davies, 393-446. New York, NY: Academic Press.
- Hinds, W.C. 1982. *Aerosol Technology*. New York, NY: John Wiley and Sons.
- Jorgenson, R. 1983. *Fan Engineering*, 8th ed. Buffalo Forge Company, Buffalo, NY.
- Leonard, J.J. 1986. Design and control of ventilation inlets

- for animal housing. Unpublished Ph.D thesis, University of Alberta, Edmonton, AB.
- Liao, C.M. and J.J.R. Feddes. 1990a. Mathematical analysis of a lumped-parameter model for describing the behavior of airborne dust in animal housing. *Applied Mathematical Modelling* 14:248-257.
- Liao, C.M. and J.J.R. Feddes. 1990b. A lumped-parameter model for predicting airborne dust concentrations in a ventilated airspace. CSAE Paper No. 90-125. Saskatoon, SK: CSAE.
- Randall, J.M. 1980. Selection of piggery ventilation systems and penning layouts based on the cooling effects of air speed and temperature. *Journal of Agricultural Engineering Research* 25:169-187.
- Van de Vate, J.F. 1972. The thickness of the stagnant air layer in aerosol contaminants and the aerodynamic diameter of aggregates of small spheres. *Journal of Colloid Interface Science* 41(2):194-197.