#4634.

This article is reprinted from the TRANSACTIONS OF THE ASAE (Vol. 33, No. 5, pp. 1693-1699, 1990)
Published by the American Society of Agricultural Engineers, St. Joseph, MI 49085-9659 USA

UPWARD VS. DOWNWARD VENTILATION AIR FLOW IN A SWINE HOUSE

N. O. Breum, H. Takai, H. B. Rom

ABSTRACT

Several ventilation system designs are in common use, and very little is known about their relative performance in achieving an acceptable livestock building air quality. A ventilation system may be characterized quantitatively from the efficiency (β^*) of the air exchange process and the effectiveness ($\in$) of the contaminant removal process. The theoretical framework is summarized and applied in an intervention study of upward versus downward air flow in a swine house. The contaminants considered were NH_3, CO_2, dust, and excessive heat. It was concluded that the air exchange efficiency of upward air flow was superior to downward air flow. For some contaminants (CO_2, excessive heat, dust) the ventilation effectiveness of upward air flow was superior to downward air flow.

INTRODUCTION

Ventilation is essential to air quality management of livestock buildings, and a number of types of ventilation design principles are in use. The air exchange process and the contaminant removal process are generally not identical, and consequently should be treated separately (Skaaret, 1986). The flow fields of air and contaminants are usually very complex, involving turbulence, so that a detailed description is extremely difficult or even impossible and experimental methods characterizing average behaviour have to be used (Niemela, 1986).

The effectiveness of the contaminant removal process may be characterized by "ventilation effectiveness", and the effectiveness of the air renewal process may be characterized by "air exchange efficiency" (Skaaret, 1986). In this context, contaminants are interpreted in general terms and, therefore, includes temperature (excessive heat causing temperatures higher than the air supply temperature). Relatively few measurements have been made simultaneously on air exchange efficiency and ventilation effectiveness.

Comparison of the efficiency of alternative ventilation systems is of vital importance for obtaining good health and high productivity in housed livestock. Therefore, an intervention study was made of the flow fields of air and contaminants in a swine house with two alternative ventilation systems designed from the principles of upward and downward air flow, respectively. The principles are shown in figure 1.

Article was submitted for publication in March 1990; reviewed and approved for publication by the Structures and Environment Div. of ASAE in July 1990.

The authors are **N. O. Breum**, M.Sc., National Institute of Occupational Health, Lersoe Parkalle 105, Copenhagen, Denmark; and **H. Takai**, Ph.D., and **H. B. Rom**, M.Sc., National Institute of Agricultural Engineering, Bygholm, Horsens, Denmark.

* Symbols are defined in Nomenclature.

VENTILATION MODELS

VENTILATION EFFECTIVENESS MODEL

A contaminant source may have its own momentum flux creating its own flow pattern. Consequently, the flow patterns of contaminants usually differ from those of fresh air. It is therefore necessary to give an indicator for contaminant removal performance of the ventilation system. The ventilation effectiveness, $\in$, is a common indicator (Niemela, 1986). The steady state, room average, ventilation effectiveness is defined as follows:

$$\in = \left[c_e(\infty) - c_s(\infty)\right] / \left[<c(\infty)> - c_s(\infty)\right] \qquad (1)$$

where

$C_e(\infty)$ = steady-state contaminant concentration at the exhaust,

$C_s(\infty)$ = steady-state concentration in the supply air, and

$<C(\infty)>$ = steady-state room average concentration.

Equation 1 reflects the room average ventilation effectiveness of the system at steady-state. If the concentration distribution is spatially nonuniform it may be difficult to measure $<C(\infty)>$, and a local ventilation effectiveness may be considered more useful. The local

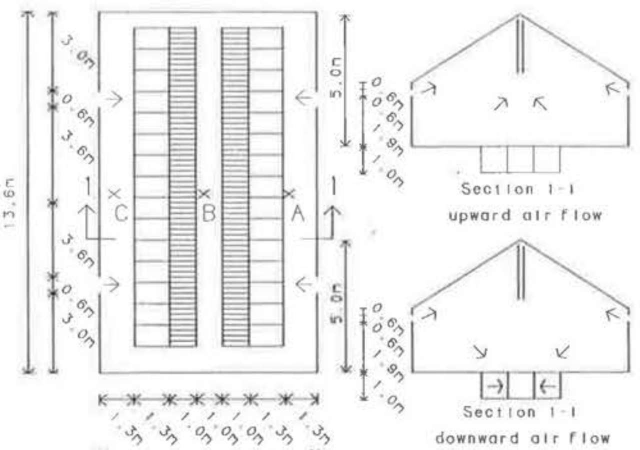


Figure 1–Layout and cross-section of an experimental swine house (not drawn to scale).

ventilation effectiveness, ϵ_p, for an arbitrary point, p, in the room can be defined as follows (Niemela, 1986):

$$\epsilon_p = \left[c_e(\infty) - c_s(\infty)\right] / \left[c_p(\infty) - c_s(\infty)\right] \quad (2)$$

where

$C_p(\infty)$ = steady-state concentration at the point p.

Steady-state concentrations may be difficult to measure in practice. For nonsteady-state situations, a local transient ventilation effectiveness, ϵ_p^{tr}, for a point, p, may be defined for a time period $t_1 - t_2$ (Niemela, 1986):

$$\epsilon_p^{tr} = \left[\int_{t_1}^{t_2} C_e(t)\, dt - \int_{t_1}^{t_2} C_s(t)\, dt\right] / \left[\int_{t_1}^{t_2} C_p(t)\, dt - \int_{t_1}^{t_2} C_s(t)\, dt\right] \quad (3)$$

It is noted that a measured local ventilation effectiveness depends heavily on the location of the measurement point, p. A high effectiveness is expected to be measured near an air supply inlet, and for complete mixing, ventilation effectiveness is 1.0. By short-circuiting, the supply air is poorly utilized and the ventilation effectiveness is less than 1.0. As a design goal for a desirable ventilation scheme, the local ventilation effectiveness for the zone of occupancy should be high.

Air Exchange Efficiency Model

Mixing processes in chemical reactor engineering are characterized by age distribution theory (Levenspiel, 1963) and the concepts of this theory may be used to characterize the air flow patterns of ventilation processes (Sandberg, 1981). Consider a mechanically ventilated room with volume V (m^3) with one or more air inlets and outlets. Ventilation capacity of supply air is Q_s (m^3h^{-1}), and ventilation capacity of exhaust air is denoted Q_e ($m^3\ h^{-1}$). It is assumed that supplied air leaves the room by the exhaust, i.e., $Q = Q_s = Q_e$ (a balanced ventilation system). The nominal time constant of the ventilation process is denoted τ_n and

$$\tau_n = V/Q \quad (4)$$

It is noted that the reciprocal of the nominal time constant is often called the air exchange rate. Elements of air entering the room remain in it for some time and then leave: their age is equal to time spent in the room. Three different populations of air may be defined (Sandberg, 1981):

- Total population of all fluid elements of air within the room,
- Local population of fluid elements of air at an arbitrary point p within the room, and
- Population of fluid elements of air leaving the room.

There is a cumulative age distribution F(t) for each of the populations mentioned, which is, for any t, the fraction of fluid elements with an age less than or equal to t. F(t) is defined over $(0,\infty)$ so that $F(O) = 0$ and $F(\infty) = 1$. The corresponding age frequency distribution f(t) is derived as:

$$f(t) = dF(t)/dt \text{ or } F(t) = \int_0^t f(t^*)\, dt^* \quad (5)$$

The mean of the distribution is μ where:

$$\mu = \int_0^\infty t\, f(t)\, dt = \int_0^\infty [1 - F(t)]\, dt \quad (6)$$

The age distribution may be experimentally determined by labelling the air using a signal-response, tracer gas technique. The signal is the injection of tracer gas and the response is the measured tracer gas concentration. Three strategies of tracer gas injection are widely used: 1) decay ("step-down"); 2) continuous injection at a constant rate ("step-up"); and 3) pulse injection (Sandberg, 1981). The decay strategy was applied in the present study. Tracer gas response may be measured at given points within the room or at the flow exit, and a recorded concentration data versus time represents an age distribution. The equation of the age distribution depends on the tracer gas injection strategy used and on the population of fluid elements considered (Breum, 1989). In the following, however, only the decay technique is discussed.

Let tracer gas be injected at a constant rate, q ($cm^3\ h^{-1}$), into the room and artificially mixed with room air. The spatially homogeneous, steady-state, tracer concentration is denoted $C_h(\infty)$. The gas injection and the mixing process is terminated at $t = 0$, and the concentration at a position p within the room at time t is $C_p(t)$. Then the cumulative age distribution $F_p(t)$ of the fluid elements of fresh air at this position is (Breum, 1989):

$$F_p(t) = 1 - C_p(t) / C_h(\infty) \quad (7)$$

The mean age, μ_p, of fluid elements passing this position, p, is:

$$\mu_p = \int_0^\infty t f_p(t)\, dt = \int_0^\infty [1 - F_p(t)]\, dt = \int_0^\infty C_p(t) / C_h(\infty)\, dt \quad (8)$$

If p is at the exhaust, the population of fluid elements leaving the room is also described by equation 8. In that case, it is noted that equation 8 also provides an estimate of τ_n (Skaaret, 1986). The concentration at the exhaust is denoted $C_e(t)$ and the age frequency distribution $\langle f(t) \rangle$ of all the fluid elements within the room is (Niemela, 1986):

$$\langle f(t) \rangle = C_e(t) / \int_0^\infty C_e(t)\, dt \quad (9)$$

and the room mean age $\langle \mu \rangle$ of all the fluid elements is:

$$\langle \mu \rangle = \int_0^\infty t\, f(t)\, dt = \int_0^\infty t\, C_e(t)\, dt / \int_0^\infty C_e(t)\, dt \quad (10)$$

Note that $Q = q/C_h(\infty)$.

By definition (Skaaret, 1986), the displacement flow pattern (plug-flow) is considered most efficient for exchange of air within a room. If the flow pattern of the room investigated were like plug-flow, the mean age of air within the room would be "low". Let this mean age be denoted $\langle \mu_d \rangle$. Then:

$$<\mu_d> = \tau_n / 2 \quad (11)$$

The actual flow pattern of the room investigated, however, may deviate from the defined ideal, and the mean age of air in the room would, therefore, be higher than $<\mu_d>$. Let this actual mean age be denoted $<\mu>$. The air exchange efficiency, β, is by definition (Skaaret, 1986):

$$\beta = <\mu_d> / <\mu> = \tau_n / (2 <\mu>) \quad (12)$$

It is noted that $0 \leq \beta \leq 1.0$. An air exchange efficiency of $\beta = 1.0$ is achieved for ideal displacement flow, complete mixing is characterized by an efficiency of 0.5, while stagnant flow yields $\beta < 0.5$.

Description of the Swine House

The swine house had a maximum capacity of 32 sows. During the study 31 sows were in the house. The estimated heat load per square meter floor area of the house was 50 W m^{-2}. A layout and a cross-section of the swine house (V = 400 m^3) are shown in figure 1. The house had two rows of pens (2 × 16) with feeding passages along the walls. The pens had a solid floor and a slotted floor over a slurry channel in the dunging area. Chopped straw was used for bedding and the sows were limit-fed twice a day (morning/afternoon).

The swine house had two alternative exhaust ventilation systems based upon different design principles: upward and downward air flow, respectively. For both ventilation systems outside air entered the room through 4 inlets (0.6•0.3 m, each) dispersed along the the sides of the house (fig. 1). Upward air flow was exhausted from an outlet at the ridge (fig. 1, section 1-1: upward air flow). Downward air flow was exhausted from the slurry channels through well dispersed outlets to the exhaust duct (fig. 1, section 1-1: downward air flow). Ventilation capacity normally was controlled by room air temperature, but could optionally be fixed at maximum and minimum capacity, respectively.

Experimental Procedure

General Design

The performance of the two alternative ventilation systems was tested at two different, but constant ventilation capacities: high (maximum capacity), and low (minimum capacity). The air supply temperature ranged from 2.7° C to 5.9° C throughout all the tests. Different levels of room temperature and animal activity were consequently accepted for the testing at the two different ventilation capacities. Animal activity (percentage of sows standing) was recorded in all tests. Activity was kept at a minimum by restricting conditions that might disturb the animals.

Normal probability plots were used for checking the environmental data for non normality. The paired t-test, and alternatively the Wilcoxon test (in case of non normal data distribution) were used for statistical analysis of data.

Two separate test periods were used for ventilation effectiveness and air exchange efficiency testing. All ventilation effectiveness tests were performed independently to eliminate any influence from the artificial air mixing process used in the air exchange efficiency tests. It can be concluded from a previous review (Heber et al., 1988) on livestock building air quality, that animal activity causes daily air quality fluctuations. Testing was consequently performed during periods with expected similar animal activity in order to minimize the influence of animal activity on the test results. It is noted, however, that a different animal activity was accepted for testing at high and low ventilation capacity, respectively.

Ventilation Effectiveness Testing

Studies (Veit et al., 1985; Heber et al., 1988) have drawn attention to the complexity of environmental quality in swine houses. The following contaminants were selected for testing in this study: aerial dust, NH_3, CO_2 and temperature. It was noted that other contaminants also may be useful for ventilation effectiveness testing, e.g., H_2S, SO_2 and moisture. For a period of 2 h, the local transient ventilation effectiveness, ϵ_p^{tr}, was estimated in the zone of occupancy at positions A-C (fig. 1) at two levels above the floor (0.5 m and 2.0 m). Data used to estimate the effectiveness were measured at the positions mentioned, the exhaust air, and the supply air. The contaminants were measured using the following techniques.

Aerial dust was collected on membrane filters (5 μm pore size) at a sampling rate of 1.9 $Lmin^{-1}$ according to standard techniques in industrial hygiene (NIOSH, 1984). The mass of collected dust was determined by weighing the filter before and after sampling. Based on tests in the laboratory the accuracy of a measured dust concentration was estimated to be ±5%. The NH_3 concentrations were measured using long term, direct reading detector tubes, and from literature the accuracy of a measured concentration was estimated to be ±15% (Draeger, 1985).

The CO_2 concentration was recorded sequentially using the multipoint measuring unit, in figure 2 (Breum and Skotte, 1986). This unit drew air continuously through the sample lines (10 mm i.d. tubing) and the sampling manifold of three-way solenoid valves using gas-tight pumps. Air from each line was delivered sequentially to the gas analyzer at a flow rate of 33 $Lmin^{-1}$. The gas was analyzed by an i.r.-analyzer (MIRAN 80, Foxboro Analytical). The use of a digital filter (Skotte et al., 1990) reduced the sequential step period of the unit to only 15 s. Based on tests in the laboratory the accuracy of the analysis was estimated to be ±5%. During an experiment the sequence of operations and the data acquisition were run by menu-driven software using a portable computer. The air temperature was measured (Pt100 transducers) sequentially (15-s step period) using the multipoint

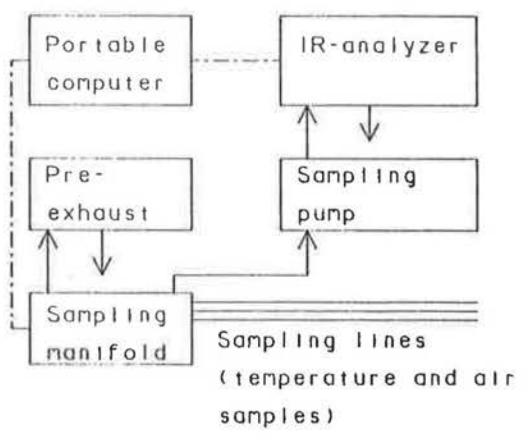


Figure 2–Multipoint measuring unit.

measuring unit. Based on tests in the laboratory the estimated accuracy was ±0.1°C.

Air Exchange Efficiency Testing

Tracer gas (SF_6) was introduced into the room at a constant flow rate controlled by a calibrated rotameter. Flow rate was 1.1 $Lmin^{-1}$ at maximum ventilation capacity and 0.13 $Lmin^{-1}$ at minimum ventilation capacity. Based on tests in the laboratory the estimated accuracy was ±3%. The tracer was artificially mixed with portable fans in room air, and the concentration was recorded at the selected positions using the previously described measuring unit (fig. 2). Preliminary tests did not show that any gases produced by swine interfered with the tracer gas analysis. When a spatially homogenous steady state tracer concentration had been reached the tracer injection and the mixing process was terminated, and the concentration decay was measured. An exponential curve-fitting procedure available with the menu-driven software was used to estimate $F_p(t)$ from the data. Numerical integration was used to estimate μ_p from equation 8 and $<\mu>$ from equation 10. The ventilation flow rate was calculated from $Q = q/C_h(\infty)$ at a calculated accuracy of ±6%. Air velocity measurements at the fan outlet is another technique of estimating the flow rate (ACGIH, 1984).

Results and Discussion

General

Ventilation capacities were nearly identical for the upward and downward air flow. The estimated maximum capacities were 2600 m^3h^{-1} and 2400 m^3h^{-1} at the upward and downward air flow, respectively. The estimated minimum capacities were 560 m^3h^{-1} and 490 m^3h^{-1} at the upward and downward air flow, respectively. Stable air movement patterns in a room depend on the heat load, height of the room, and the air change rate (Croome, 1989). To overcome rising buoyancy driven air flow the required air change rate to obtain a stable air movement pattern in a room with downward air flow is twice as large as that of upward air flow (Croome, 1989). The required ventilation capacity in the swine house for stable upward air flow is estimated (Croome, 1989) at 14400 m^3h^{-1}; consequently, the ventilation processes investigated in this project should be considered unstable. It is noted that the required ventilation capacity far exceeds Danish recommendations (Anon, 1985) for swine house ventilation (15-100 m^3h^{-1} per sow).

TABLE 1. Animal activity (percentage of standing sows) in a swine house

Direction of air flow	Ventilation capacity	
	Maximum	Minimum
Upward	88±4*	42±15
Downward	82±9	34±15

* Mean ± standard deviation.

As ventilation capacity was increased, the air temperature within the swine house decreased (Table 2). The recorded animal activity is shown in Table 1. A substantial increased activity was observed at the high ventilation capacity compared to the low ventilation capacity. As air quality fluctuations are related to animal activity (Heber et al., 1988), a comparison of test data measured at different ventilation capacities were excluded from further analysis.

CO_2 Ventilation Effectiveness

Table 2 shows the range of measured CO_2 concentrations. The CO_2 concentration was lower ($P < 0.05$) with upward air flow as compared to downward air flow. This finding applies for ventilation at low as well as high capacity.

The estimated local transient CO_2 ventilation effectiveness, ϵ_p^{tr}, was calculated for all the experiments, figure 3. The CO_2 ventilation effectiveness of upward air flow compared to downward air flow was higher ($P < 0.05$). This result is consistent with results from numerical simulation of CO_2 concentrations in a room occupied by humans (Homma and Takei, 1987). It was noted, however, that the simulated air supply inlet for upward air flow was at floor level while in the present study inlets were 1.9 m above the floor.

A vertical CO_2 ventilation effectiveness stratification was observed ($P < 0.05$) except for upward air flow at low ventilation capacity. This stratification was consistent with results from numerical simulation of transient CO_2 concentrations in a room occupied by humans (Homma and Takei, 1987). A transient as well as a steady-state CO_2 stratification was observed for upward air flow. Only a transient stratification was observed for downward air flow, and to a lesser degree.

NH_3 Ventilation Effectiveness

Table 2 shows the range of measured NH_3 concentrations. Compared to upward air flow the NH_3

TABLE 2. Range of environmental data from a swine house

Air flow direction	Ventilation capacity: Maximum				Minimum			
	CO_2 (ppm)	NH_3 (ppm)	Dust (mg/m^3)	Temp (°C)	CO_2 (ppm)	NH_3 (ppm)	Dust (mg/m^3)	Temp (°C)
Upward	950-1210	2.0-4.6	0.3-0.5	10.7-13.3	4040-4380	6.2-12.1	0.3-0.9	17.1-18.7
Downward	1250-1550	1.7-3.0	0.2-1.5	8.8-10.8	4090-4630	9.1-13.2	0.4-0.9	16.7-18.5

concentration was decreased ($P < 0.05$) by selecting downward air flow. This result applied only for high ventilation capacity. The NH_3 concentration was increased ($P < 0.05$) by selecting downward air flow for low ventilation capacity. Data measured in an experimental swine house (Olsen, 1987) demonstrated decreased NH_3 concentrations for downward air flow compared to upward air flow. However, the measured decrease depended on the ventilation capacity. The NH_3 concentrations for an upward air flow may be lower than for a downward air flow at low ventilation capacity (Olsen, 1987). Since manure is the ammonia pollutant source, investigations on methods of source control by inhibiting the release of ammonia are desired. It is noted that by selecting peat as bedding, the concentration of NH_3 in a poultry house was reduced by 62% (Manninen et al., 1989).

Figure 3 shows the calculated local transient NH_3 ventilation effectiveness, ϵ_p^{tr}, for all the experiments. At high ventilation capacity, there was an improved ($P < 0.05$) NH_3 ventilation effectiveness of downward air flow compared to upward air flow. At low ventilation capacity there was an improved ($P < 0.05$) NH_3 ventilation effectiveness of upward air flow compared to a downward air flow. From the literature, no data are readily available for comparison, and further studies in this field are needed.

Temperature Ventilation Effectiveness

Table 2 shows the range of measured air temperatures. Compared to downward air flow the temperature level was greater ($P < 0.05$) by selecting upward air flow. This result applied to maximum ventilation capacity. At low ventilation capacity no ($P < 0.05$) influence of air flow direction on temperature level was demonstrated.

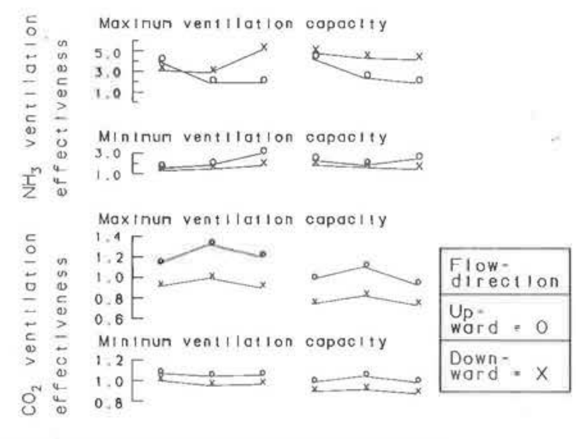
In figure 4 the calculated local transient temperature ventilation effectiveness for all the experiments is shown. At both ventilation capacities, there was an improved ($P < 0.05$) temperature ventilation effectiveness of upward air flow compared to downward air flow. This result is consistent with results from an experimental room, although it is noted that the supply air inlet was at floor level for the upward air flow testing (Sandberg and Sjoberg, 1983).

A vertical ventilation effectiveness stratification was observed ($P < 0.05$), except for upward air flow at minimum ventilation capacity. Considering temperature a contaminant, vertical ventilation effectiveness stratification is consistent with results from numerical simulation of the transient CO_2 concentration in a room occupied by humans (Homma and Takei, 1987) and with data measured on site in an electroplating plant (Breum et al., 1989).

Dust Ventilation Effectiveness

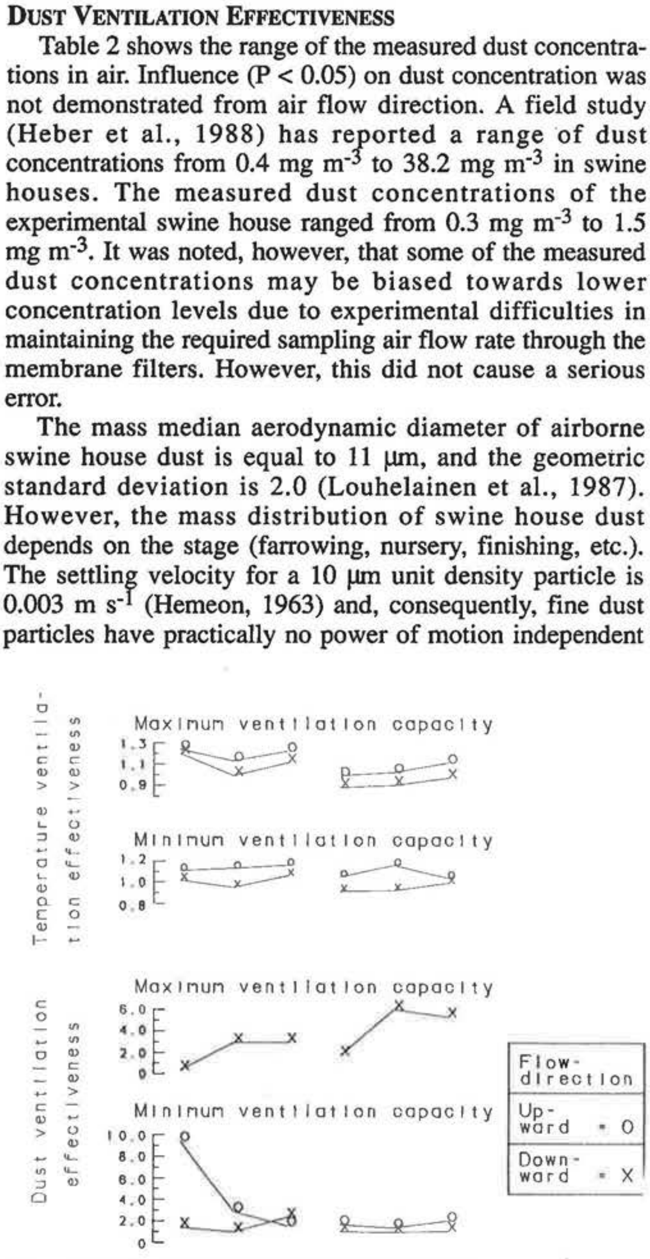
Table 2 shows the range of the measured dust concentrations in air. Influence ($P < 0.05$) on dust concentration was not demonstrated from air flow direction. A field study (Heber et al., 1988) has reported a range of dust concentrations from 0.4 mg m^{-3} to 38.2 mg m^{-3} in swine houses. The measured dust concentrations of the experimental swine house ranged from 0.3 mg m^{-3} to 1.5 mg m^{-3}. It was noted, however, that some of the measured dust concentrations may be biased towards lower concentration levels due to experimental difficulties in maintaining the required sampling air flow rate through the membrane filters. However, this did not cause a serious error.

The mass median aerodynamic diameter of airborne swine house dust is equal to 11 µm, and the geometric standard deviation is 2.0 (Louhelainen et al., 1987). However, the mass distribution of swine house dust depends on the stage (farrowing, nursery, finishing, etc.). The settling velocity for a 10 µm unit density particle is 0.003 m s^{-1} (Hemeon, 1963) and, consequently, fine dust particles have practically no power of motion independent



Position	A	B	C	A	B	C
Height above the floor, m	0.5	0.5	0.5	2.0	2.0	2.0

Figure 3–Estimated local transient CO_2 and NH_3 ventilation effectiveness, respectively. Each line represents the local ventilation effectiveness at a level above the floor as stated at bottom of the figure.



Position	A	B	C	A	B	C
Height above the floor, m	0.5	0.5	0.5	2.0	2.0	2.0

Figure 4–Estimated local transient dust and temperature ventilation effectiveness, respectively. Each line represents the local ventilation effectiveness at a level above the floor as stated at bottom of the figure.

of the air in which they are suspended. The calculated local transient dust ventilation effectiveness is shown in figure 4. Data are missing for the upward air flow with maximum ventilation capacity due to experimental failure in measuring the exhaust air dust concentration. Upward air flow with minimum ventilation capacity showed an improved ($P < 0.05$) dust ventilation effectiveness compared to downward air flow. The improved dust ventilation effectiveness of upward air flow is consistent with the results stated above for other contaminants (CO_2 and temperature).

Air Exchange Efficiency

Table 3 shows the calculated air exchange efficiency. Included in the table is the estimated room mean age of air. Air exchange efficiency ranged from 53% to 65%, and no apparent difference in room average performance of the two alternative air flow directions was observed. This result is consistent with data from an experimental room with buoyancy driven flow, where disturbances in the room caused mixing in the room (Andegiorgis, 1988). It is well known (Homma and Takei, 1987; Heiselberg and Nielsen, 1988) that the influence of free convection around a heated body increases its relative effect on air currents in a room when room air movement is reduced. A criterion for a stable air flow pattern has been developed in terms of room height, heat load and air change rate (Croome, 1989). With undisturbed buoyancy driven flow in an experimental chamber, an elevated air exchange efficiency was achieved with ventilation systems using upward air flow compared to systems using downward air flow (Sandberg and Sjoberg, 1983). It is emphasized, however, that if the rising convective currents are not balanced by the supply of incoming air, recirculation back down into the occupied zone can occur and, consequently, influence the mixing process in the room (Breum et al., 1989). Only few air exchange efficiency data measured on-site are available. An efficiency of 54% was reported for upward air flow in a printing plant (Breum, 1988). In an auditorium with downward air flow, the efficiency was 28% and 23% with 50 and 120 occupants in the room, respectively (Drangsholt, 1987).

Although a ventilation process taken as a room average may be characterized as complete mixing, a spatial nonuniform air exchange efficiency may exist (Breum, 1988). The local mean age of air is an indicator of the local air exchange efficiency, and the estimated mean ages are shown in figure 5. From this age parameter and for both ventilation capacities, upward air flow showed ($P < 0.05$) an improved air exchange efficiency compared to downward air flow. This result is consistent with data from an intervention study in an electroplating plant (Breum et al., 1989). At the electroplating plant a vertical stratification of the mean age of air occurred with upward air flow, only. In the swine house, however, no ($P < 0.05$) stratification was observed.

TABLE 3. Calculated air exchange efficiency (β) and room mean age (<μ>) of air in a swine house

	Ventilation capacity			
	Maximum		Minimum	
Direction of air flow	<μ> min	β %	<μ> min	β %
Upward	8.1	57	39	55
Downward	7.9	65	47	53

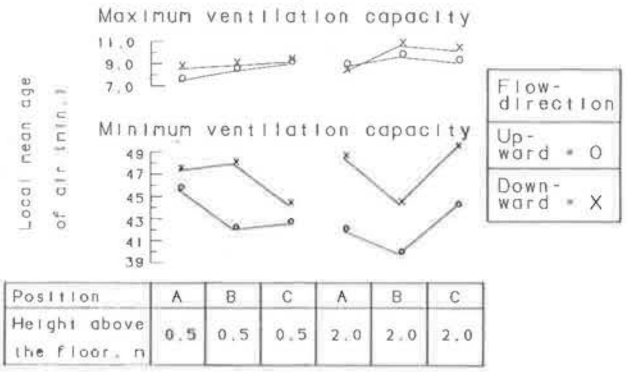


Figure 5–Estimated local mean age of air. Each line represents the local mean age of air at a level above the floor as stated at bottom of the figure.

Correlation of Air and Contaminant Flow Fields

It is well known that the flow patterns of contaminants may differ from those of fresh air. However, the more distributed, homogeneous and passive (no momentum) the contaminant sources are, the better the correlation is between the air exchange efficiency and the ventilation effectiveness (Skaaret, 1986; Holmberg et al., 1987). Locally upward air flow improved the air exchange efficiency compared to downward air flow. Compared to downward air flow, upward air flow also showed an improved ventilation effectiveness for some contaminants (CO_2, temperature, and dust). This result, however, does not apply to contaminants in general such as the NH_3 ventilation effectiveness of downward air flow at a high (but not a low) ventilation capacity exceeded that of upward air flow.

Conclusion

In the zone of occupancy the air exchange efficiency of upward air flow was superior to downward air flow.

For some contaminants (CO_2, excessive heat, dust) the ventilation effectiveness of upward air flow was also superior to downward air flow, but this result does not apply to contaminants in general.

At a high ventilation capacity the NH_3 ventilation effectiveness of downward air flow was superior to upward air flow, but at a low ventilation capacity upward air flow was again superior to downward air flow.

The maximum ventilation capacity was according to common practice but far below the rate required for obtaining a stable air flow pattern.

The analytical models of air exchange efficiency and ventilation effectiveness were useful in characterizing flow fields of air and contaminants in swine buildings.

References

ACGIH, 1984. Industrial ventilation, a manual of recommended practice. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.

Andegiorgis, T. 1988. Ventilation employing displacement flow. In *Proc. Healthy Buildings '88'*, eds. B. Berglund and T. Lindvall, 3:31-37.

Anon. 1985. Håndbog for driftsplanlægning. Landbrugets Informationskontor. (In Danish)

Breum, N.O. and J. Skotte. 1986. Måling af ventilationseffektivitet. Arbejdsmiljøfondet, Copenhagen (In Danish).

Breum, N.O. 1988. Air exchange efficiency of displacement ventilation in a printing plant. *Ann. Occup. Hyg.* 32(4): 481-488.

Breum, N.O. 1989. The air exchange efficiency of a lecture hall. In *Ventilation '88'*, ed. J.H. Vincent, 307-317. Pergamon Press.

Breum, N.O., F. Helbo and O. Laustsen. 1989. Dilution versus displacement ventilation – An intervention study. *Ann. Occup. Hyg.* 33(3): 321-329.

Croome, D.J. 1989. A comparison of upward and downward air distribution systems. In *Ventilation '88'*, ed. J.H. Vincent, 433-438. Pergamon Press.

Drangsholt, F. 1987. Ventilation by demand. *Proc. 4th Int. conf. indoor air quality and climate*, 3: 180-186.

Draeger, 1985. *Detector tube handbook*, 6th ed. Lubeck, FRG: Draegerwerk AG.

Heber, A.J., M. Stroik, J.L. Nelssen and D.A. Nichols. 1988. Influence of environmental factors on concentrations and inorganic content of aerial dust in swine finishing buildings. *Transactions of the ASAE* 31(3): 875-881.

Heiselberg, P. and P.V. Nielsen 1988. Flow conditions in a mechanically ventilated room with a convective heat source. 9th AIVC Conf.

Hemeon, W.C.L. 1963. *Plant and Process Ventilation.* New York: Industrial Press Inc.

Holmberg, R.B., K. Folkesson, L.B. Stenberg and G. Jansson 1987. Experimental comparison of indoor climate using various air distribution methods. *Proc. 4th Int. conf. indoor air quality and climate*, 3: 307-312.

Homma, H. and H. Takei. 1987. Influence of free convection of occupants' metabolic heat on vertical distribution of carbon dioxide in classroom. *Proc. Roomvent '87.*

Levenspiel, O. 1963. Chemical Reaction Engineering. New York: John Wiley.

Louhelainen, K., P. Vilhunen, J. Kangas and E.O. Terho. 1987. Dust exposures in piggeries. *European J. Respiratory Diseases* 71 (suppl. 152): 8090.

Manninen, A., J. Kangas, M. Linnainmaa and H. Savolainen. 1989. Ammonia in Finnish poultry houses: Effects of litter on ammonia levels and their reduction by technical binding agents. *Am. Ind. Hyg. Assoc. J.* 50(4): 210-215.

Niemela, R. 1986. Characterization of the performance of industrial ventilation systems by the tracer gas technique. Ph.D. thesis, Dept. of Physics, University of Helsinki, Finland.

NIOSH. 1984. *NIOSH manual of analytical methods*, 3rd ed. DHHS (NIOSH) Pub. No. 84-100. Cincinnati, OH: National Institute for Occupational Safety and Health.

Olsen, J. 1987. Arbejdsmiljøvenlige staldsystemer. Agri Contact. (In Danish)

Sandberg, M. 1981. What is ventilation efficiency? *Building and Environment* 16(2): 123-135.

Sandberg, M. and M. Sjobjerg. 1983. A comparative study of the performance of different heating and ventilation systems. *Proc. 3rd Int. conf. indoor air quality and climate*, 5: 59-64.

Skaaret, E. 1986. Contaminant removal performance in terms of ventilation effectiveness. *Environmental International* 12: 419-427.

Skotte, J., N.O. Breum and T. Schneider. 1990. Improving an i.r. tracer gas analyser by digital filtering. *Building and Environment* 25(2): 151-154.

Veit, H.P., E.T. Kornegay and E.R. Collins. 1985. Air quality, pig health and performance in triple deck nurseries. *Transactions of the ASAE* 28(4): 1259-1264.

Nomenclature

C	concentration
$C(\infty)$	steady-state concentration
F(t)	cumulative age distribution
f(t)	age frequency distribution
Q	volumetric flow rate
q	tracer gas injection rate
t	time
V	volume of the room
β	air exchange efficiency
ϵ	ventilation effectiveness
μ	mean
τ	time constant

Subscripts and Other Symbols

e	exhaust air
h	spatially homogeneous
n	nominal
s	supply air
p	arbitrary point in the room
$\langle\mu\rangle$	room average