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Improving the Work Environment in Livestock Buildings

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LIST OF ABBREVIATIONS

ACGIH	=	American Conference of Governmental Industrial Hygienists
AMCA	=	Air Movement and Control Association
ANOVA	=	Analysis of variance
ASAE	=	American Society of Agricultural Engineers
ASHRAE	=	American Society of Heating, Refrigerating and Air-Conditioning Engineers
$C_{exhaust}$	=	Dust concentration at the exhaust (mg/m^3)
C_{inlet}	=	Dust concentration at the air inlet (mg/m^3)
C_m	=	Mean dust concentration in the room (mg/m^3)
C_p	=	Dust concentration at the point of interest (mg/m^3)
CV	=	Coefficient of variation
E_o	=	Overall relative ventilation effectiveness (dimensionless)
E_p	=	Relative ventilation effectiveness at the point of interest in the airspace (dimensionless)
GSD	=	Geometric standard deviation
IAQ	=	Indoor air quality
IOM	=	Institute of Occupational Medicine
MMD	=	Mass median diameter

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ABSTRACT

This research was conducted in an attempt to improve the work environment in livestock buildings. The overall aim was to develop and test a local ventilation system that will provide for more effective removal of air contaminants away from the worker's breathing zone.

The effectiveness of conventional air inlets was first evaluated in a pilot-scale experimental facility. Three supply air inlets (one-way ceiling, two-way ceiling, and sidewall) were compared at three levels of ventilation rates in terms of relative ventilation effectiveness for airborne dust. The dust concentrations were measured with inhalable dust samplers, from which the relative ventilation effectiveness and the spatial variability in dust concentrations were obtained. General findings were as follows:

- In general, ventilation rate or air exchange rate had limited effects on the relative ventilation effectiveness and spatial uniformity of dust concentrations.
- The central alley had lower relative ventilation effectiveness than the pens for all three types of air inlets and for all ventilation rates. The pens receiving the fresh outside air first had the highest relative ventilation effectiveness.
- The three air inlets differed in terms of ventilation effectiveness. The one-way ceiling inlet, in which the supply air jet was directed away from the exhaust fan, had the highest overall relative ventilation effectiveness, although it also had the highest spatial variability in dust concentration. The sidewall air inlet, on the other hand, had the most uniform dust concentration; however, it also had the lowest overall relative ventilation effectiveness.

Various designs of local supply ventilation systems were then developed and evaluated in the experimental facility. The designs involved local supply ventilation in which fresh air was introduced down the central alley, representing the workers'

breathing zone. Most of the designs resulted in low dust concentration or high relative ventilation effectiveness at the alley, although, in some designs, the dust concentration in one of the pens (representing the animal occupied zone) was extremely high indicating that little fresh air was being moved into that zone. The final design that was adopted and further evaluated in this research involved a perforated air inlet located near the center of the ceiling in combination with either the one-way or two-way conventional ceiling air inlet. This local supply ventilation system was designed expressly to introduce fresh air down the alley to the workers' breathing zone and reduce dust concentration in that zone. Comparing this system with the conventional air inlets illustrates the success of the local system in achieving that goal.

SIGNIFICANT FINDINGS

Evaluation of the ventilation effectiveness of three conventional ceiling air inlets (one-way ceiling, two-way ceiling, sidewall) indicated that, in general, ventilation rate had limited effects on the relative ventilation effectiveness and spatial uniformity of inhalable dust concentrations. More important, the central alley had lower relative ventilation effectiveness than the pens for all three types of conventional air inlets and for all ventilation rates; the pens receiving the fresh outside air first had the highest relative ventilation effectiveness. Further, the three conventional air inlets differed in terms of ventilation effectiveness. The one-way ceiling inlet, in which the supply air jet was directed away from the exhaust fan, had the highest overall relative ventilation effectiveness, although it also had the highest spatial variability in dust concentration. The sidewall air inlet, on the other hand, had the most uniform dust concentration; however, it also had the lowest overall relative ventilation effectiveness.

The above findings further reinforced the need to develop alternative designs to ensure adequate air quality at or near the workers' breathing zone. Local supply ventilation, in which air was introduced at or near the workers' breathing zone, in combination with a conventional air inlet proved promising. Compared with the conventional air inlets, the local supply ventilation system had lower dust concentration at the alley and more uniform dust concentrations within the room. These results suggest that bringing fresh air down the workers' breathing zone could improve the ventilation effectiveness at that zone and possibly improve the working conditions for the workers in swine confinement buildings.

USEFULNESS OF FINDINGS

This research illustrates the potential of local supply ventilation in ensuring adequate air quality at or near the workers' breathing zone. In particular, a system in which fresh or clean air is introduced down the alley to the workers' breathing zone in combination with a conventional ceiling air inlet performed the best in terms of relative ventilation effectiveness at the alley, overall relative ventilation effectiveness for the room, and spatial variability in dust concentrations. Such local supply or zonal ventilation system could be used for farrowing and nursery rooms for swine. Additional research is necessary to establish guidelines and parameters for successful implementation and operation of the local supply or zonal ventilation system in livestock confinement buildings. Such research should involve a combination of experimental and numerical simulation research. In addition, field-scale demonstration of the system is warranted.

SCIENTIFIC REPORT

Ventilation systems for livestock confinement buildings rely on adequate dilution and air mixing to control indoor air quality (IAQ). However, ideal mixing rarely occurs in actual facilities, resulting in stagnant regions with higher concentrations of air contaminants (dust and gases) than in other regions. Given that air contaminants are generally produced at or below the animal occupied zone, a possible solution to minimizing health risks to workers is to introduce clean air at or near their breathing zone through local or zonal ventilation.

In industrial work environments, local supply ventilation system is used to control or minimize exposure of workers to various air contaminants (ASHRAE, 1995). In this system, clean air is supplied toward the workers' breathing zone to create comfortable conditions and/or reduce the concentration of air contaminants in that zone. This system has not been adopted in livestock confinement buildings, largely because livestock ventilation design has focused on providing adequate environmental conditions for the housed animals. By locating the air supply at or near the workers' breathing zone, it may be possible to reduce the concentration of air contaminants in the breathing zone.

There has been limited research investigating the effectiveness of local supply ventilation and other alternative systems in improving IAQ for swine buildings. Breum et al. (1990) studied two ventilation systems for swine buildings - upward and downward airflow. For both systems, outside air entered the room through four air inlets dispersed along the sides of the building. For the upward airflow system, the air was exhausted at the ridge; for the downward airflow system, the air was exhausted at the manure slurry channels below the floor. The upward airflow system had better air exchange efficiency and greater ventilation effectiveness for carbon dioxide and dust, but it had lower ventilation effectiveness for ammonia than the downward airflow system.

Van't Klooster et al. (1993) showed a 50% reduction in dust concentration for a supply air inlet located near the nose height of the workers versus an air inlet that was a counterbalanced baffle at eave height. In addition, they observed a 78% reduction in dust concentration when the air entered the room at the floor level (low supply) and was expelled through a duct running along the length of the room above the floor slats (low exhaust). This low supply, low exhaust system was also reported in another study to be more effective in removing airborne dust compared to the high supply, high exhaust system (Aarnink and Wagemans, 1997).

This research was conducted in an attempt to improve the working environment in livestock buildings. The overall aim was to develop and test a local ventilation system that will provide for more effective removal of air contaminants away from the workers' breathing zone. The effectiveness of conventional air inlets was first evaluated in an experimental room during the first year of the research. During the remainder of the research project, various designs of local supply ventilation systems were developed and evaluated in the experimental room. The designs involved local supply ventilation in which fresh air was introduced down the central alley.

The scientific report is organized in two sections. The first (Study 1) dealt with the evaluation of the conventional air inlets while the second (Study 2) dealt with local supply ventilation systems in concert with conventional air inlets.

Study 1 – Conventional air inlets

Objectives

Three conventional supply air inlets (one-way ceiling, two-way ceiling, and sidewall) were compared at ventilation rates of 0.1, 0.5, 0.7, and 1.0 m^3/s. The dust concentrations were measured with inhalable dust samplers, from which the relative ventilation effectiveness at various locations, the overall relative ventilation effectiveness for the airspace, and the spatial variability in dust concentrations were obtained. Specific objectives were:

- To compare the one-way ceiling, two-way ceiling, and sidewall air inlets in terms of their ventilation effectiveness for airborne dust, and
- To determine the effects of ventilation rates on the performance of these conventional air inlets.

Methods

Experiments were conducted in a test chamber that represented a section of a swine building.. The chamber was 3.6 m long, 2.4 m high, and 7.2 m wide (fig. 1); it had been used in previous studies of air quality in swine buildings (Puma et al., 1999a; 1999b). The test chamber had four pens and an alley. Mock-up pigs were represented by 16 galvanized steel pipes with a diameter of 20 cm and a length of 2.8 m. Each pipe was capped at both ends and supported by flat steel bars at a height of about 15 cm above the floor. The mock-ups occupied about 2.3% of the total room volume.

Experimental design. Table 1 summarizes the experiments and experimental conditions for evaluating and comparing the conventional air inlets. Two major factors were considered: the type of air inlet and the ventilation rate. The air inlets were the two-way ceiling, the one-way ceiling, and the sidewall inlets. The two-way and the one-way ceiling inlets were both box-type inlets and installed in the center of the ceiling. The two-way ceiling inlet had two supply air jets directed in opposite directions, whereas the one-way ceiling inlet had one supply jet directed to the wall opposite the exhaust fan. The sidewall inlet was a rectangular opening, 28 cm × 118 cm, on the wall opposite the exhaust fan; a baffle at an angle of about 45° directed the supply air jet.

The following ventilation rates were considered: 0.1, 0.5, 0.7, and 1.0 m^3/s for the two-way ceiling and sidewall inlets and 0.1, 0.5, and 0.7 m^3/s for the one-way ceiling inlet. A variable speed fan with a diameter of 0.61 m was set up in the test chamber and connected to a fan motor speed controller to deliver the desired ventilation rate. The ventilation rate was measured with a propeller anemometer upstream of the exhaust fan. The anemometer was based on the principle that a freely rotating propeller would rotate at a speed that is directly proportional to air speed or flow rate (Maghirang et al., 1998). It had two blades 20 cm long that were attached to a central hub. It was mounted in a section of a round duct with a diameter of 64 cm. A photoelectric sensor combined with a power supply/display unit monitored and recorded the rotational speed of the blades. The device was first tested in a fan test facility to establish the linear relationship between the rotational speed of the device and volumetric flow rate. The fan test facility was designed and constructed according to the specifications set forth by AMCA Standard 210 (AMCA, 1985).

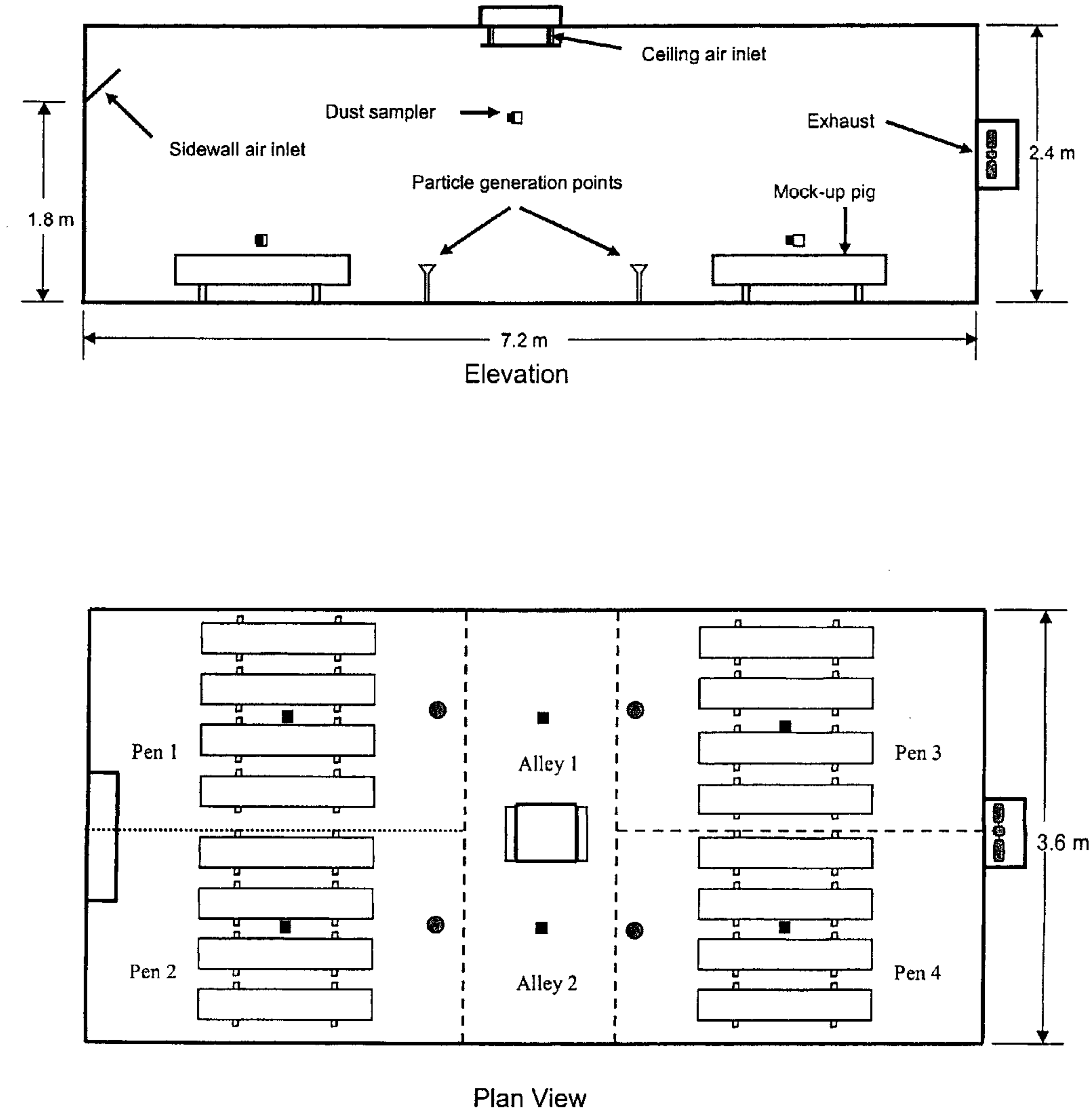


Figure 1. Schematic diagram of the test room showing the sampling locations.

Table 1. Experimental design for evaluating and comparing the conventional air inlets (Study 1).

Type of Air Inlet	Ventilation Rate (m^3/s)	Number of Replicates	Temperature Range (°C)	Relative Humidity Range (%)
Two-way ceiling	0.1	3	23 - 26	20 - 41
	0.5	3		
	0.7	3		
	1.0	3		
One-way ceiling	0.1	3	22 - 25	21 - 42
	0.5	3		
	0.7	3		
Sidewall	0.1	3	23 - 25	26 - 52
	0.5	3		
	0.7	3		
	1.0	3		

Dust generator. A dust generator (Puma et al., 1999a; 1999b) introduced the test particles (i.e., corn starch powder) into the room. The particles had a mass median diameter (MMD) of 15 μm and a geometric standard deviation (GSD) of 2.0 as measured with a cascade impactor. Measurement of the particle size distribution with a cascade impactor in an experimental swine nursery showed a MMD ranging from 10 to 19 μm and GSD ranging from 2 to 5 (Maghirang et al., 1997).

The dust generator was located outside the test room; particles were emitted into the room through four plastic tubes, one in each pen (fig. 1). A plastic funnel with a series of perforated metal sheets was connected to the end of each tube to disperse the particles into the room. All experiments had the same settings for the dust generator to provide a consistent and approximately equal dust generation rate.

Measurement of dust and related parameters. The dust concentration at each sampling location was measured with the IOM (Institute of Occupational Medicine, Edinburgh) dust sampler (Mark and Vincent, 1986). The sampler (SKC Inc., Eighty Four, Penn.), which meets the ACGIH (1985) criteria for inhalable particulate matter sampling, has been used to measure the dust concentrations in livestock buildings (Phillips et al., 1998; Puma et al., 1998; Predicala et al., 2001). It incorporated a reusable filter cassette, a 25 mm filter, and a sampling head designed to measure exposure to total airborne particles. It was operated at a sampling airflow rate of 2 L/min, which was maintained using a flowmeter with a regulator (Model SSV-50, Dwyer Instruments, Michigan City, Ind.). All samplers and flowmeters were connected to a multiport manifold and a vacuum pump. The flowmeters, manifold, and pump were located outside the test room to minimize any interference with room airflow.

As illustrated in figure 1, each pen had one sampler located at about 0.50 m above the floor; these sampling locations were denoted pen 1, pen 2, pen 3, and pen 4. The service alley had two samplers at a height of about 1.50 m; these sampling locations were denoted alley 1 and alley 2. In addition, the exhaust had two samplers, and the inlet had one sampler.

The prevailing airflow pattern in the test room was visualized with tracer smoke generated by a smoke gun (Model 15-092T-T, E. Vernon Hill, Inc., Benecia, Calif.). The temperature and humidity inside the test chamber also were measured with a thermo-hygrometer. Ranges of temperature and humidity for all experiments were 22°C to 26°C and 20% to 52%, respectively (table 1).

Sampling procedure. Before each experiment, the room was cleaned by wiping all surfaces with wet mops and running the exhaust fan for about 2 h. The dust generator then was operated at the desired setting. About 30 min thereafter, when quasi-equilibrium within the test room has been reached (Puma et al., 1999a; 1999b), dust sampling commenced and lasted for a period between 60 and 180 min. The sampling period was selected so that the accumulated dust on the filters was greater than 0.5 mg, the amount necessary so that the concentration measurement would not be affected unduly by the weight stability of the filter (Hinds, 1982).

The collection filters, which had been preconditioned in a constant humidity container (25°C, 50% relative humidity) for 24 h and then weighed, were conditioned again for an additional 24 h. This was done to minimize the effect of humidity on their weights. The conditioned filters then were weighed in an electronic microbalance (Model AG245, Mettler-Toledo, Hightstown, N.J.) with a sensitivity of ±0.01 mg.

Analysis of data. The dust concentration at each sampling location was calculated by dividing the amount of dust collected by the product of sampling flow rate and sampling period. Because of symmetry in the ventilated airspace including pen arrangement, flow pattern, and particle generation, pens 1 and 2, pens 3 and 4, and alleys 1 and 2 were assumed to have the same or similar dust concentrations. Paired t-tests at the 5% level confirmed this assumption. The dust concentrations for the two pens on the same side of the alley, that is, pens 1 and 2 (left) and pens 3 and 4 (right), then were averaged to determine the concentrations for those combinations of pens. The concentrations for the service alley (alleys 1 and 2) also were combined. From the dust concentration, the relative ventilation effectiveness (E_p) was determined (Liddament, 1987; Breum et al., 1990; Zhang et al., 2001):

$$E_p = \frac{C_{exhaust} - C_{inlet}}{C_p - C_{inlet}} \qquad (1)$$

where

E_p = Relative ventilation effectiveness at the point of interest in the airspace (dimensionless)

$C_{exhaust}$ = Dust concentration at the exhaust (mg/m^3)

C_{inlet} = Dust concentration at the air inlet (mg/m^3)

C_p = Dust concentration at the point of interest (mg/m^3)

E_p expresses how the system's ventilation ability varies among the different parts of the room. Its value is always positive and can be greater than 1.0. For example, when the room conditions are well mixed, C_p will be uniform throughout the room and will be equal to $C_{exhaust}$, so $E_p = 1.0$ throughout the room. A high E_p in the occupied zone is a characteristic of a good ventilation scheme.

The mean dust concentration (C_m) for the sampling locations over the pens and alley was calculated for each replicate. From the C_m value, the overall relative ventilation effectiveness (E_o) was calculated (Breum et al., 1990; Liddament, 1987):

$$E_o = \frac{C_{exhaust} - C_{inlet}}{C_m - C_{inlet}} \qquad (2)$$

E_o provides an "averaged" value for the entire enclosure. Like E_p, a high E_o is characteristic of a good ventilation system. With well-mixed conditions, $C_m = C_{exhaust}$, so that $E_o = 1.0$.

In addition, the coefficient of variation (CV) of the dust concentrations in the pens and alley was computed for each replicate. The CV provides a measure of the spatial variability in dust concentrations and the degree of mixing within the room. With perfect or ideal mixing, the concentrations will be uniform throughout the room, and the CV will be zero. With poor or insufficient mixing, the concentrations will vary with location, and the CV will be high.

The effects of ventilation rate and type of air inlets on E_p, E_o, and CV were determined using standard analysis of variance (ANOVA) techniques and a 5% level of significance. The least significance difference method was used to determine statistical significance of differences among means. All statistical analyses were done with PC-SAS (SAS Institute, Cary, N.C.)

Results and Discussion

Two-way ceiling air inlet. For the two-way ceiling air inlet, the mean E_p values and ranges were 1.56 (1.17 to 2.50) for pens 1 and 2, 1.22 (1.08 to 1.60) for pens 3 and 4, and 0.58 (0.35 to 0.80) for the alley. The effect of ventilation rate on the mean E_p for each of these locations was not significant ($p > 0.05$). The ANOVA also indicated that these means were significantly ($p < 0.05$) different from each other (fig. 2). The room air movement associated with this inlet accounts for the lower E_p in the alley than in the pens. Figure 3a shows the prevailing room air movement for this air inlet; it consisted of two large counter-rotating circulation zones. With this air movement, the "fresh" outside air moved from the inlet to the pens and then to the alley, transporting the dust generated from the dust sources to the alley.

The mean E_o was 0.93, and the range was 0.68 to 1.12. Ventilation rate had limited but significant ($p<0.05$) effects on E_o (fig. 4); however, no increasing or decreasing trend occurred in E_o with ventilation rate. For example, the ventilation rate of 0.7 m^3/s had the highest mean E_o, which was not significantly ($p > 0.05$) different from that for the ventilation rate of 0.1 m^3/s. The mean E_o values for the other two ventilation rates (0.5 and 1.0 m^3/s) were not significantly ($p > 0.05$) different from that for the ventilation rate of 0.1 m^3/s.

The mean CV for the sampling locations was 0.46, and the range was 0.30 to 0.68. Although CV was rather high, spatial gradients in dust concentration have been observed in livestock buildings (Barber et al., 1991). They are expected because dust sources are not distributed uniformly and conditions are not well mixed. This spatial gradient or CV did not vary significantly ($p > 0.05$) with ventilation rate (fig. 5). Thus, mixing within the room, and consequently uniformity in dust concentration, cannot be improved further by increasing the ventilation rates from 0.1 to 1.0 m^3/s for this air inlet.

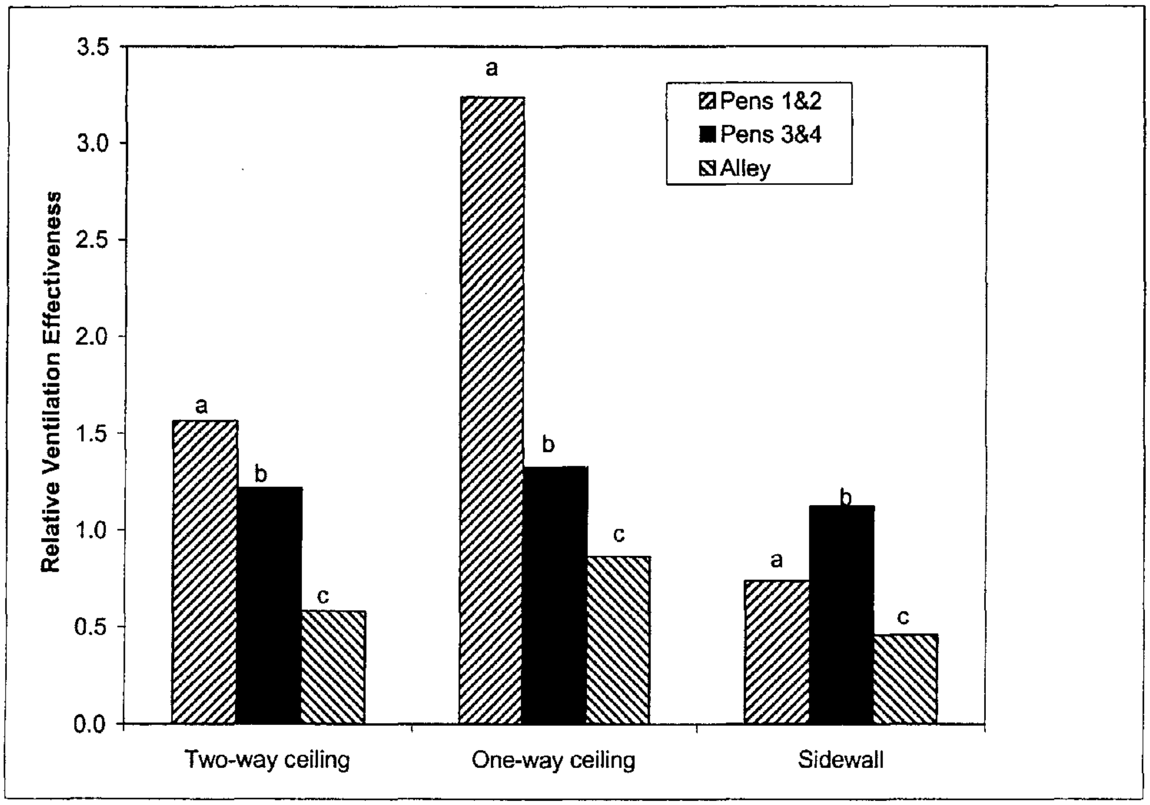


Figure 2. Relative ventilation effectiveness for each air inlet and for different sampling locations. Means within the same type of air inlet with a common letter are not significantly different at the 5% level.

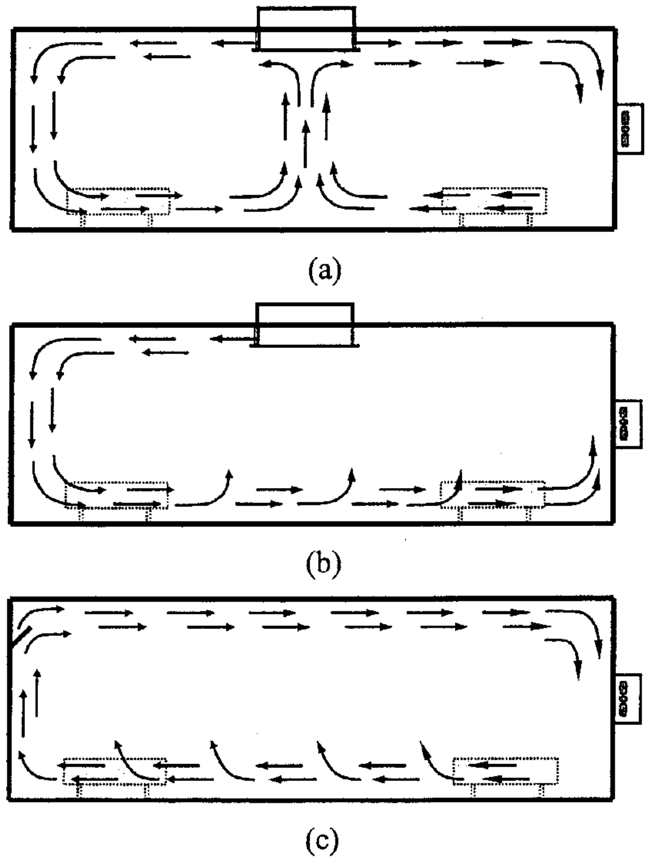


Figure 3. General airflow patterns for the different air inlets: (a) two-way ceiling, (b) one-way ceiling, and (3) sidewall. Arrow lengths do not represent the relative magnitude of the air velocities.

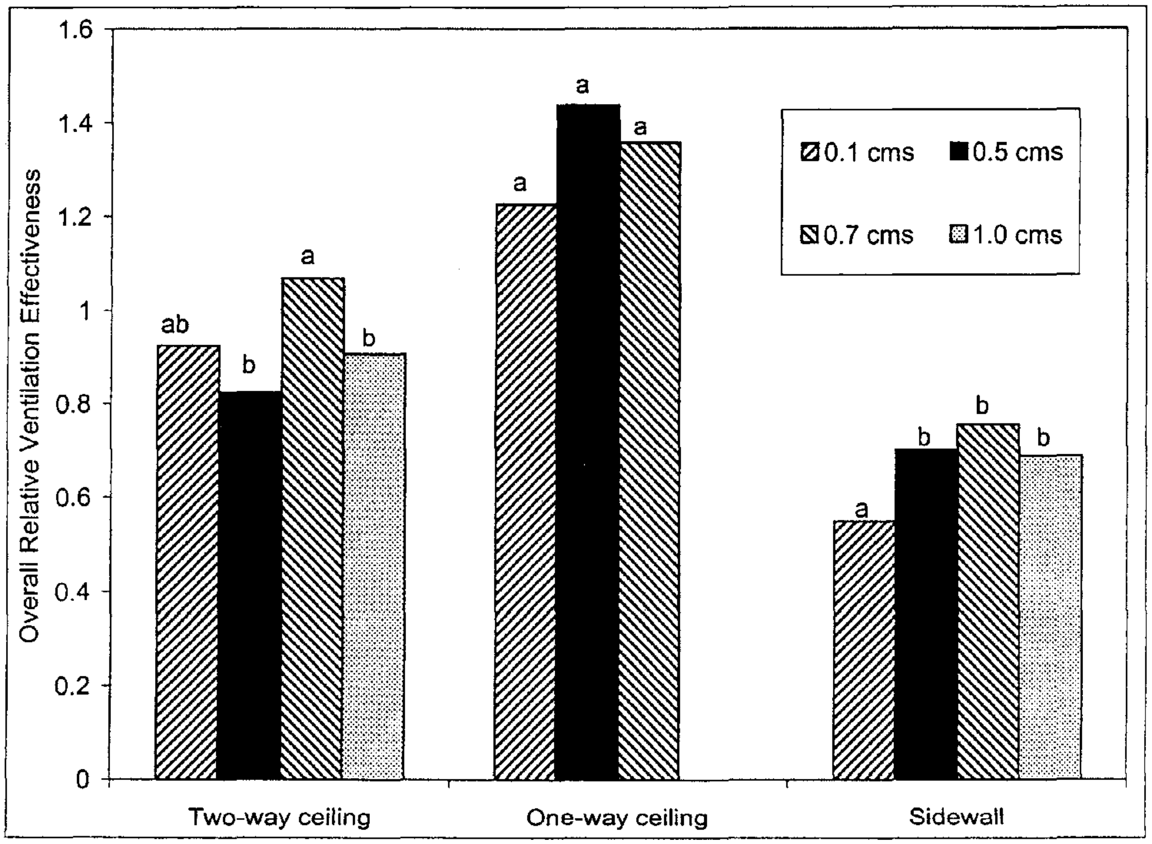


Figure 4. Overall relative ventilation effectiveness for each air inlet and for each ventilation rate (in m^3/s or cms). Means with a common letter within each type of inlet are not significantly different at the 5% level.

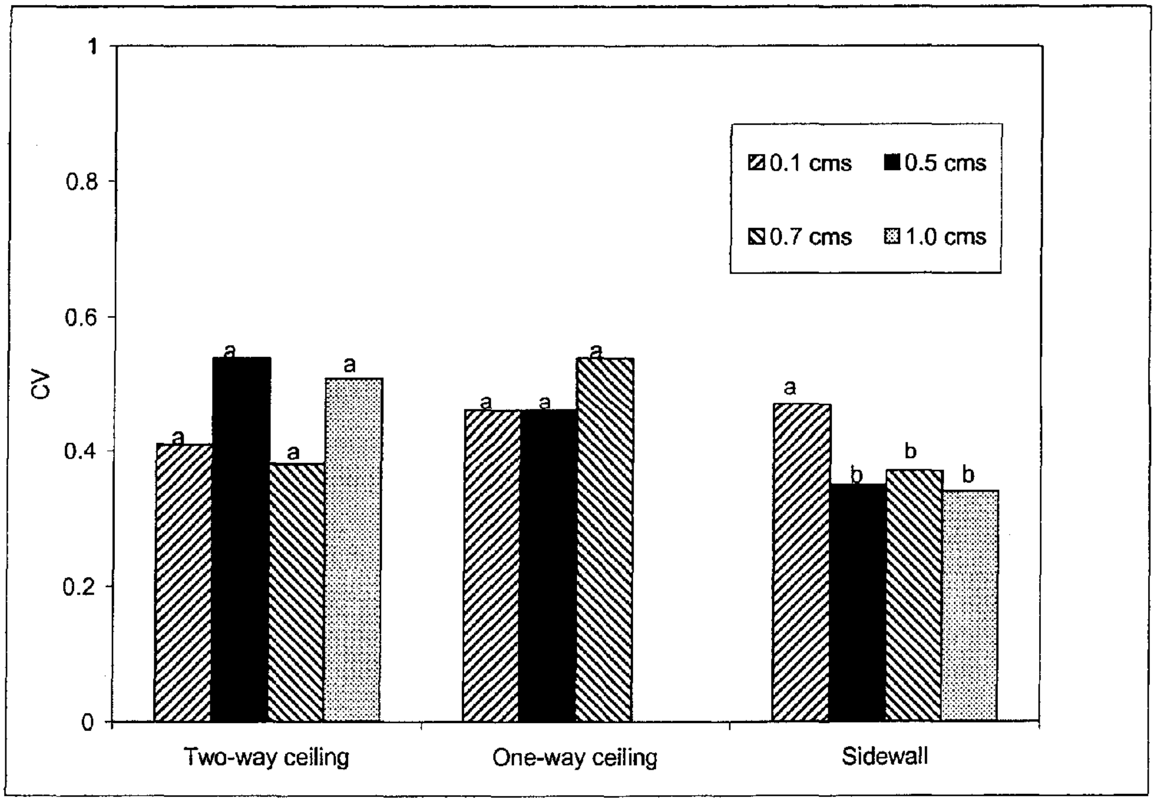


Figure 5. Coefficients of variation (CV's) for the sampling locations for each air inlet and for each ventilation rate (in m^3/s or cms). Means with a common letter are not significantly different at the 5% level.

One-way ceiling air inlet. The mean E_p values and ranges were 3.24 (2.14 to 5.36) for pens 1 and 2, 1.33 (1.01 to 1.69) for pens 3 and 4, and 0.86 (0.64 to 1.13) for the alley. Similar to the case of the two-way ceiling air inlet, these means were significantly ($p < 0.05$) different, although the differences were more pronounced for this air inlet (fig. 2). These differences can be explained partly by the prevailing air movement, which is illustrated in figure 3b. A large counterclockwise circulation zone was observed; the supply air moved from the inlet to the left side of the room (pens 1 and 2) and then to the right side of the room (alley and pens 3 and 4). This air movement would transport the dust from the left side of the room to the alley and the right side of the room; consequently, the dust concentration in the left side of the room would be lower. The ANOVA also showed that the effect of ventilation rate for each of these locations was not significant ($p > 0.05$).

The overall mean E_o was 1.34, and the range was 1.01 to 1.87. The relatively higher E_o compared to the two-way ceiling air inlet indicates that this air inlet is effective in removing contaminants from the locations considered. In contrast to the two-way ceiling air inlet, ventilation rate did not significantly affect the E_o for this inlet (fig. 4). Thus, the overall effectiveness of the ventilation system equipped with a one-way ceiling air inlet cannot be improved further by decreasing or increasing ventilation rate, at least within the range considered in this study.

The overall mean CV was 0.48, and the range was 0.41 to 0.55. Similar to the two-way ceiling air inlet, the ventilation rate effect on CV was not significant ($p > 0.05$) (fig. 5).

Sidewall air inlet. The mean E_p values and ranges were 0.74 (0.44 to 0.87) for pens 1 and 2, 1.12 (0.92 to 1.42) for pens 3 and 4, and 0.46 (0.29 to 0.53) for the alley. Similar to the ceiling air inlets, these means were significantly ($p < 0.05$) different (fig. 2). For this inlet, however, pens 3 and 4 had higher mean E_p than pens 1 and 2. Again, the prevailing air movement, illustrated in figure 3c, can account for these differences. The general air movement was clockwise. The supply air moved from the inlet to the right side of the room (pens 3 and 4) and then to the left side of the room (alley and pens 1 and

2). With this air movement, the dust generated from the dust sources would be transported from pens 3 and 4 to the alley and pens 1 and 2.

The overall mean E_o for the sidewall air inlet was 0.67, and the range was 0.45 to 0.78. The overall mean CV was 0.38, and the range was 0.25 to 0.52. For this inlet, ventilation rate had a significant ($p < 0.05$) effect on E_o (fig. 4) and CV (fig. 5). The lowest ventilation rate (0.1 m^3/s) had the lowest mean E_o and the highest mean CV; the other three ventilation rates did not show any significant difference ($p>0.05$) in E_o or CV.

<u>Comparison of the conventional air inlets.</u> The three air inlets were significantly ($p < 0.05$) different in terms of the mean E_p for pens 1 and 2, the pens farthest from the exhaust fan. For this location, the one-way ceiling air inlet had the highest mean E_p, followed by the two-way ceiling air inlet and then by the sidewall air inlet. The three air inlets also differed significantly ($p < 0.05$) in the mean E_p for the alley, with the one-way ceiling air inlet having the highest mean E_p for this location. The inlets were not significantly ($p > 0.05$) different in mean E_p for pens 3 and 4. Note that these pens were located near the exhaust, indicating that the location of the exhaust could impact the relative ventilation effectiveness in the area or zone nearby.

The one-way ceiling air inlet had a significantly ($p < 0.05$) higher mean E_o (1.34) than either the two-way ceiling air inlet (0.93) or the sidewall air inlet (0.67) (fig. 6). This observation can be explained partly by the short-circuited airflow pattern for the two-way ceiling and sidewall air inlets. Short-circuiting of air can occur if the inlet air jet is directed towards and is close to the exhaust (Randall and Boon, 1994). The flow visualization with smoke showed that a fraction of the supply air from these two air inlets passed across the ceiling to the exhaust and the opposite wall and was removed from the general circulation area (fig. 3a and 3c). Although it is generally accepted that the position of the exhaust does not affect the pattern of airflow (Randall, 1975; Albright, 1990), this short-circuited pattern further indicates the possible impact on ventilation effectiveness of exhaust placement in relation to the inlet location. Zhang et al. (2001) also observed the significant influence of outlet location on ventilation effectiveness.

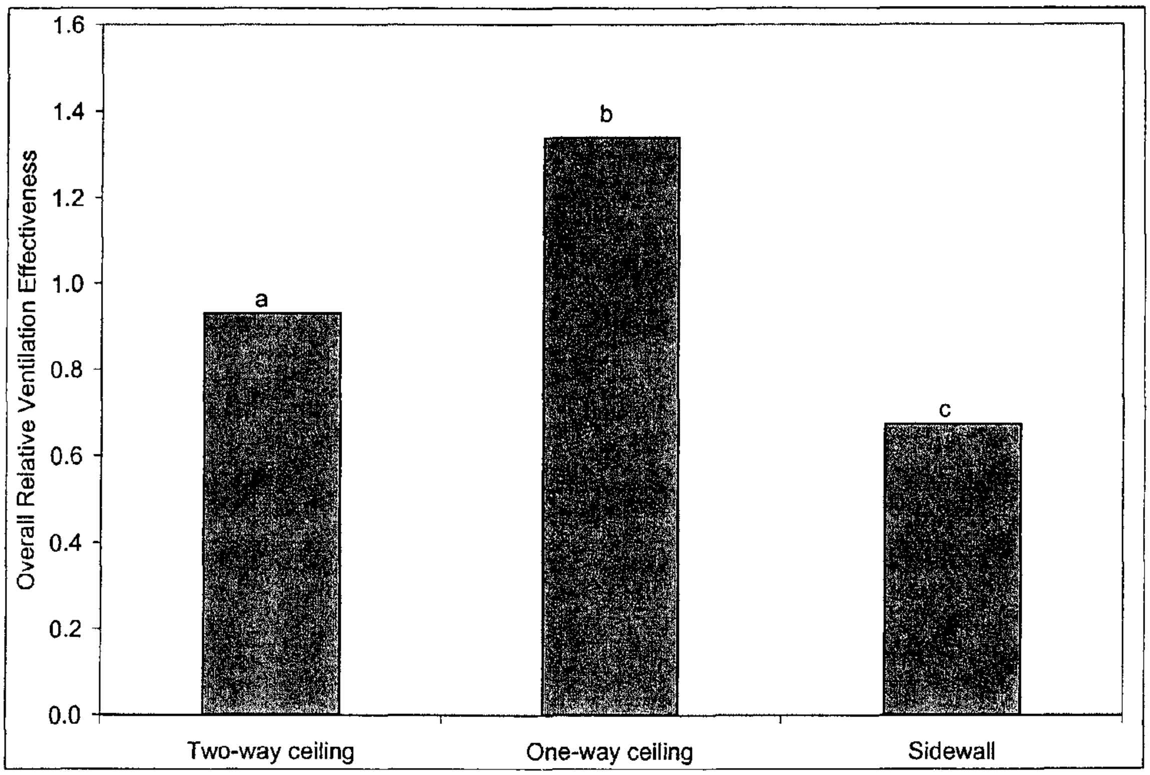


Figure 6. Overall relative ventilation effectiveness for the three air inlets. Means with a common letter are not significantly different at the 5% level.

The ANOVA also indicated some difference in spatial variability of dust concentrations, as indicated by the mean CV values. The one-way ceiling air inlet had the highest CV of 0.48 (fig. 7), which was not significantly different ($p>0.05$) from that of the two-way ceiling air inlet (0.46). The sidewall air inlet had the most uniform dust concentrations, and the mean CV of 0.38 was significantly ($p < 0.05$) different from those of both ceiling air inlets.

Conclusions

Study 1 was conducted to evaluate the relative ventilation effectiveness and spatial variability in dust concentrations in an experimental test chamber as affected by the type of conventional air inlet and ventilation rate. General findings are as follows:

- In general, ventilation rate had limited effect on the relative ventilation effectiveness and spatial uniformity of inhalable dust concentrations.
- The alley had lower relative ventilation effectiveness than the pens for all three types of air inlets and for all ventilation rates. The pens receiving the outside air first had the highest relative ventilation effectiveness.
- The three air inlets differed in terms of ventilation effectiveness. The one-way ceiling air inlet had the highest overall relative ventilation effectiveness of the three air inlets ($E_o = 1.34$); however, it also had the largest spatial variability in dust concentration (CV = 0.48). The sidewall air inlet had the most uniform dust concentration (CV = 0.38); however, it had the smallest relative ventilation effectiveness ($E_o = 0.67$).

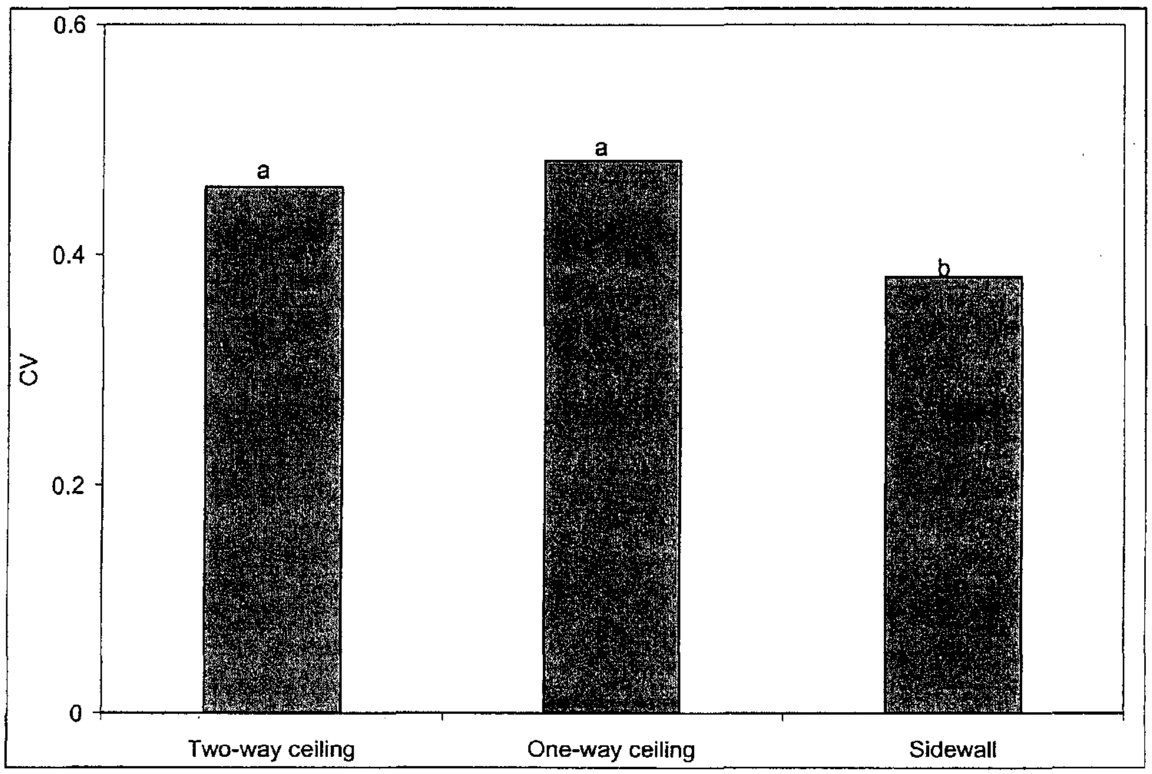


Figure 7. Coefficients of variation (CV's) of the dust concentrations for the three air inlets. Means with a common letter are not significantly different at the 5% level.

Study 2 – Local supply ventilation system

Objective

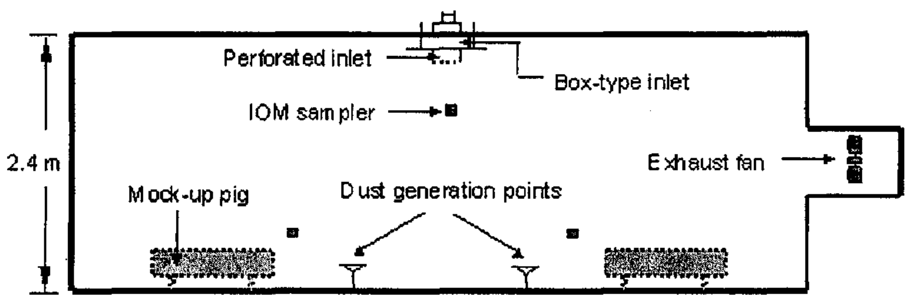
Study 1 reinforced the need to develop alternative ventilation systems for livestock buildings. One alternative ventilation system that could minimize health risks in confinement buildings is local supply or zonal ventilation system. The objective of this study was to evaluate the effectiveness of local supply or zonal ventilation in controlling dust concentration in livestock confinement buildings. The effect of exhaust location on ventilation effectiveness was also considered. Conventional supply air inlets and local supply ventilation systems were evaluated in the pilot-scale experimental facility and compared in terms of their ventilation effectiveness for airborne dust and spatial variability in dust concentration.

Methods

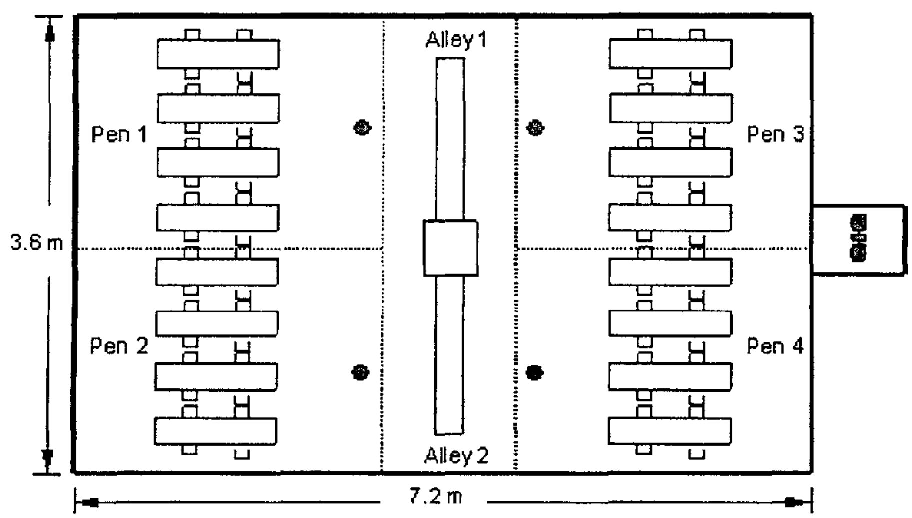
Test facility. All experiments were conducted in the same pilot -scale facility as Study 1 (fig. 8). As noted above, the facility represented a section of a swine building; it had four pens (pens 1, 2, 3 and 4) and a central service alley. Mock-up pigs were represented by 16 galvanized steel pipes with a diameter of 0.20 m and a length of 2.8 m. Each pipe was capped at both ends and supported by flat steel bars at a height of about 0.15 m above the floor. The total volume of the mock-ups was 2.3% of the room volume.

A variable speed fan connected to a fan motor speed controller delivered the desired room ventilation rate of 0.70 m^3/s. This rate was monitored with a vane anemometer positioned upstream of the exhaust fan (Maghirang et al., 1998).

A dust generator introduced corn starch powder into the room. The generated test particles had a MMD of 15 μm and a GSD of 2.0 as measured with a cascade impactor. These values were within the ranges of MMD's and GSD's obtained from a swine nursery (Maghirang et al., 1997). The dust generator was located outside the test room; particles were emitted into the room through four plastic tubes, one in each pen (fig. 8). A plastic funnel with a series of perforated metal sheets was connected to the end of each tube to disperse the particles into the room. All experiments had the same setting for the dust generators to provide a consistent and approximately equal dust generation rate.



Elevation



Plan View

Figure 8. Schematic diagram of the test chamber showing the air inlets and sampling locations.

Local supply ventilation designs. Several designs were considered and are described in Table 2. In one design, the ceiling inlet in Study 1 was modified by drilling small holes at the bottom to facilitate downward airflow. Tests showed higher dust concentration at the alley than in the pens, indicating that not enough air was being moved to the alley. Therefore, this design was dropped from consideration and further testing. The other designs were perforated inlets formed from metal sheets. The inlets were 3 m long, 0.9 m wide, and 0.20 m high and were installed on the ceiling. The two sides and the bottom were perforated with a 58% opening. Several adjustments were made on this inlet to achieve the desired velocity and airflow pattern. For example, in one design, a baffle was added to distribute airflow to the entire length of the inlet. In another design, the baffle was relocated to deflect part of the airflow sideways. Still another modification was the addition of a separate supply fan to deliver air either to the alley or to the pens. In general, the perforated inlets performed well in terms of the dust concentration at the alley relative to the concentration in the pens (Table 2). However, the dust concentrations in the pens were considerably higher than those observed for conventional air inlets, indicating that not enough air was being moved to the pens. As such, this design was also dropped from further consideration.

Preliminary tests on the combination of the perforated air inlet (with downward airflow) and the conventional air inlet proved promising. This design was then tested further (Table 3) and compared with the conventional air inlets. The conventional box-type ceiling air inlets were the same as the ceiling air inlets tested in Study 1. Box1, the one-way ceiling air inlet, had one air jet directed to the wall opposite the exhaust fan; box2, the two-way ceiling air inlet, had two supply air jets directed in opposite directions. The local supply ventilation system consisted of introducing clean air downward toward the central alley in combination with a box type ceiling air inlet. The local system had a rectangular duct (2.4 m x 0.20 m x 0.15 m) with a perforated bottom to facilitate downward airflow. With local1, the downward airflow was combined with the one-way ceiling air inlet; with local2, the downward airflow was combined with the two-way ceiling air inlet. A separate supply fan was connected to the local system to deliver the desired downward airflow to the alley. Approximately 19% of the total airflow was provided by the local system through the separate supply fan.

Table 2. Preliminary designs of the local supply ventilation system.

General Type of Local Supply System	Flow Conditions	General Observations/Findings
One-way box ceiling with holes at the bottom (for downward airflow)	Flow consisted of one horizontal ceiling jet and one low velocity airflow to the alley.	Dust concentration was highest (or ventilation effectiveness was lowest) at the alley.
Two-way box ceiling with holes at the bottom (for downward airflow)	Flow consisted of two horizontal ceiling jets and one low velocity airflow to the alley.	Dust concentration was highest (or ventilation effectiveness was lowest) at the alley.
Two-way perforated inlet (no supply fan, low exhaust)	Flow consisted of one horizontal ceiling jet and one vertical airflow to the alley.	Dust concentration at the alley was low, however, concentration at one of the pens was quite high.
Three-way perforated inlet (no supply fan, low exhaust, with baffle adjustments)	Flow consisted of two horizontal ceiling jets and one vertical airflow to the alley. Baffles were added and adjusted to obtain the desired airflow pattern.	Dust concentration at the alley was low, however, concentration at one of the pens was quite high.
Two-way perforated inlet (with supply fan – either to the pen or to the alley, low exhaust)	A supply fan was added to provide supplemental vertical airflow to the alley.	Dust concentration at the alley was low, however, concentration at one of the pens was quite high.
Three-way perforated inlet (with supply fan to direct airflow to the alley, low exhaust)	A supply fan was added to provide supplemental vertical airflow to the alley.	Dust concentration at the alley was low, however, concentration at one of the pens was quite high.

Table 3. Experimental design for study 2.

Ventilation System	Exhaust Location	Number of Replicates	Temperature (°C)	Relative Humidity (%)
Conventional box-type ceiling air inlet				
Box1 (one-way)	Wall	3	22-25	21-42
Box2 (two-way)	Wall	3	23-26	20-41
Box2 (two-way)	Floor	3	25-26	19-20
Local supply ventilation				
Local1 (downward airflow plus one-way ceiling air inlet)	Wall	3	25-26	18
Local2 (downward airflow plus two-way ceiling air inlet)	Wall	3	25-26	20-22
Local 2 (downward airflow plus two-way ceiling air inlet)	Floor	3	25-26	20-21

For the box1 and local1 systems, the exhaust was located at the center of one wall (fig. 8). For the box2 and local2 systems, two exhaust locations were considered: (1) wall and (2) floor. The wall exhaust is presented in figure 8. Exhaust for the floor exhaust system was located in the center of the room at floor level.

For each air inlet, prevailing air movement in the room was visualized with smoke sticks. The ambient air temperature and relative humidity were measured with a thermo-hygrometer.

Measurement of dust and related parameters. The protocols for measuring dust concentrations in Study 1 were followed. Dust was collected from eight sampling locations (fig. 8). Sampling locations at the pens were designated as pens 1, 2, 3, and 4, and those at the service alley were denoted as alleys 1 and 2. Dust was also collected at the supply air and exhaust. Dust concentration at the sampling locations was measured gravimetrically with the inhalable dust sampler (Mark and Vincent, 1986). It was operated at a sampling airflow rate of 2.0 L/min over a 60-min period. Dust collection filters were conditioned for 24 h in a small conditioning chamber maintained at 25°C and 50% relative humidity before and after sampling. Filters were weighed in a microbalance with a sensitivity of 0.01 mg.

Analysis of data. The dust concentration at each sampling location was calculated by dividing the amount of dust collected by the product of sampling flow rate and sampling period (60 min). Pen arrangement, airflow pattern, and dust generation, dust concentrations were symmetrical for pens 1 and 2, pens 3 and 4, and alleys 1 and 2. Therefore, dust concentration data were combined and the average dust concentration calculated for each combination. From the dust concentration, the relative ventilation effectiveness (E_p) was determined (equation 1). The dust concentrations for the pens and alley were averaged to determine the mean dust concentration for the test room (C_m) for each replicate. From the C_m values, the overall relative ventilation effectiveness (E_o) was calculated (equation 2). In addition, the coefficient of variation (CV) of the dust concentrations in the pens and alley was calculated.

The effects of the type of ventilation system or supply air inlet and the location of the exhaust on E_P, E_o, and CV were determined using standard ANOVA techniques with a 5% level of significance. The least significant difference method was used to determine statistical significance of differences among means. All statistical analyses were done with PC-SAS (SAS Institute, Cary, NC).

Results and Discussion

Box1 air inlet. Mean E_p for box1 was 3.47 for pens 1 and 2, 1.35 for pens 3 and 4, and 0.85 for the alley. Means were significantly different between pens 1 and 2 and pens 3 and 4 ($p<0.05$) (fig. 9). The general air movement shown in figure 10a could partly explain this observation. With the prevailing air movement, the supply air moved in a counterclockwise direction from the air inlet to pens 1 and 2 and then to the alley and pens 3 and 4. With this air flow pattern, the dust would be transported from the left side of the room (pens 1 and 2) to the alley and the right side of the room (pens 3 and 4). Consequently, the left side of the room (i.e., pens1 and 2) would have lower dust concentration and higher relative ventilation effectiveness than the other locations.

The overall mean E_o for this air inlet was 1.36, ranging from 1.27 to 1.44 (fig. 11). The mean CV for dust concentration was 0.54, ranging from 0.52 to 0.55 (fig. 12). The relatively high CV indicates non-uniform distribution of air among the sampling locations as described above.

Box2 air inlet. For the box2 air inlet, mean E_p was 1.83 for pens 1 and 2, 1.33 for pens 3 and 4, and 0.69 for the alley (fig. 9). There was no significant ($p>0.05$) difference between pens 1 and 2 and pens 3 and 4. As in the case of box1 air inlet, the alley had the lowest E_p, but it was not significantly ($p>0.05$) different from that of pens 3 and 4. Again, the difference in ventilation effectiveness can be attributed in part to the prevailing air movement in the room, which had two counter-rotating circulation zones converging in the central alley (fig. 10b). With this air movement pattern, the supply air moved from the air inlet to the pens, transporting the dust generated near the pens to the alley. Consequently, dust concentration was higher and E_p was lower in the alley than in the pens.

The mean E_o and CV were 1.07 and 0.38, respectively (fig. 11 and 12). Contributing to the lower CV for the box2 air inlet was the better ventilation in pens 3 and 4 due to the fresh air introduced to this section.

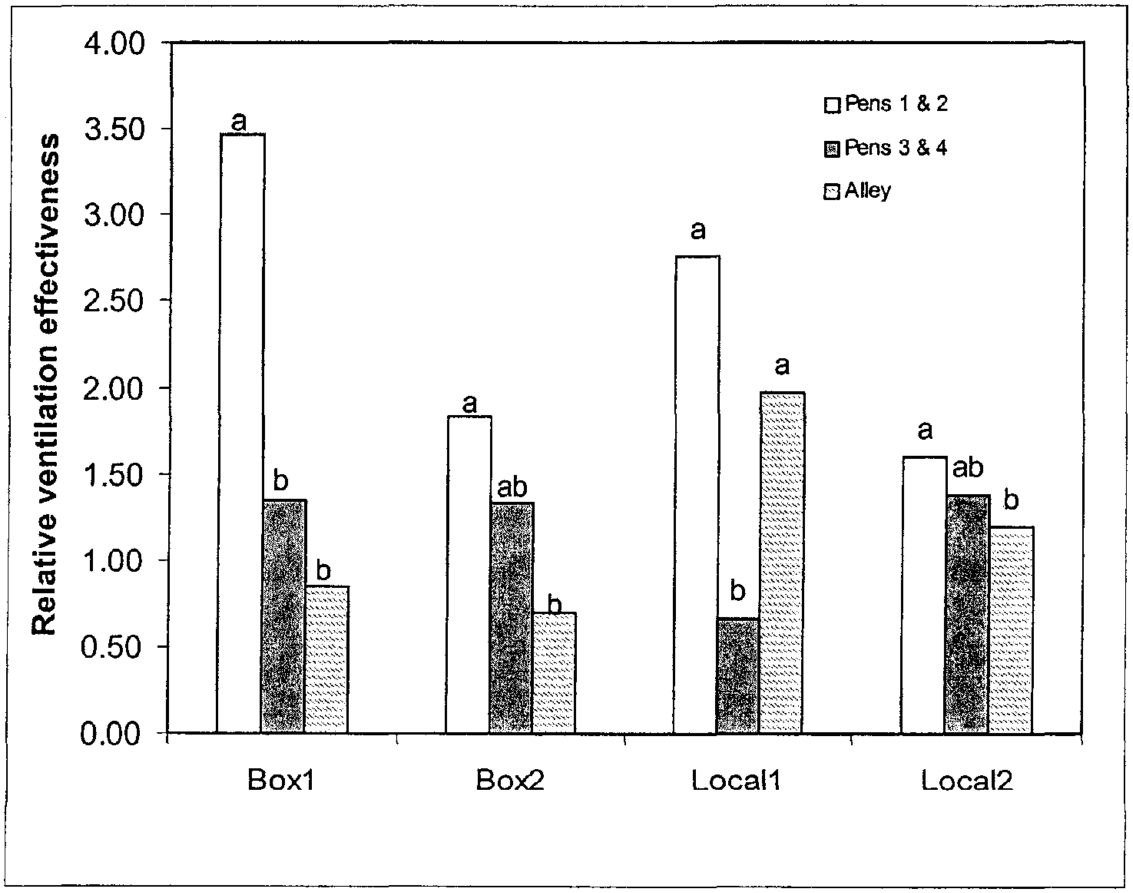


Figure 9. Relative ventilation effectiveness for each sampling location and air inlet. Means with a common letter within each type of air inlet are not significantly different at the 5% level.

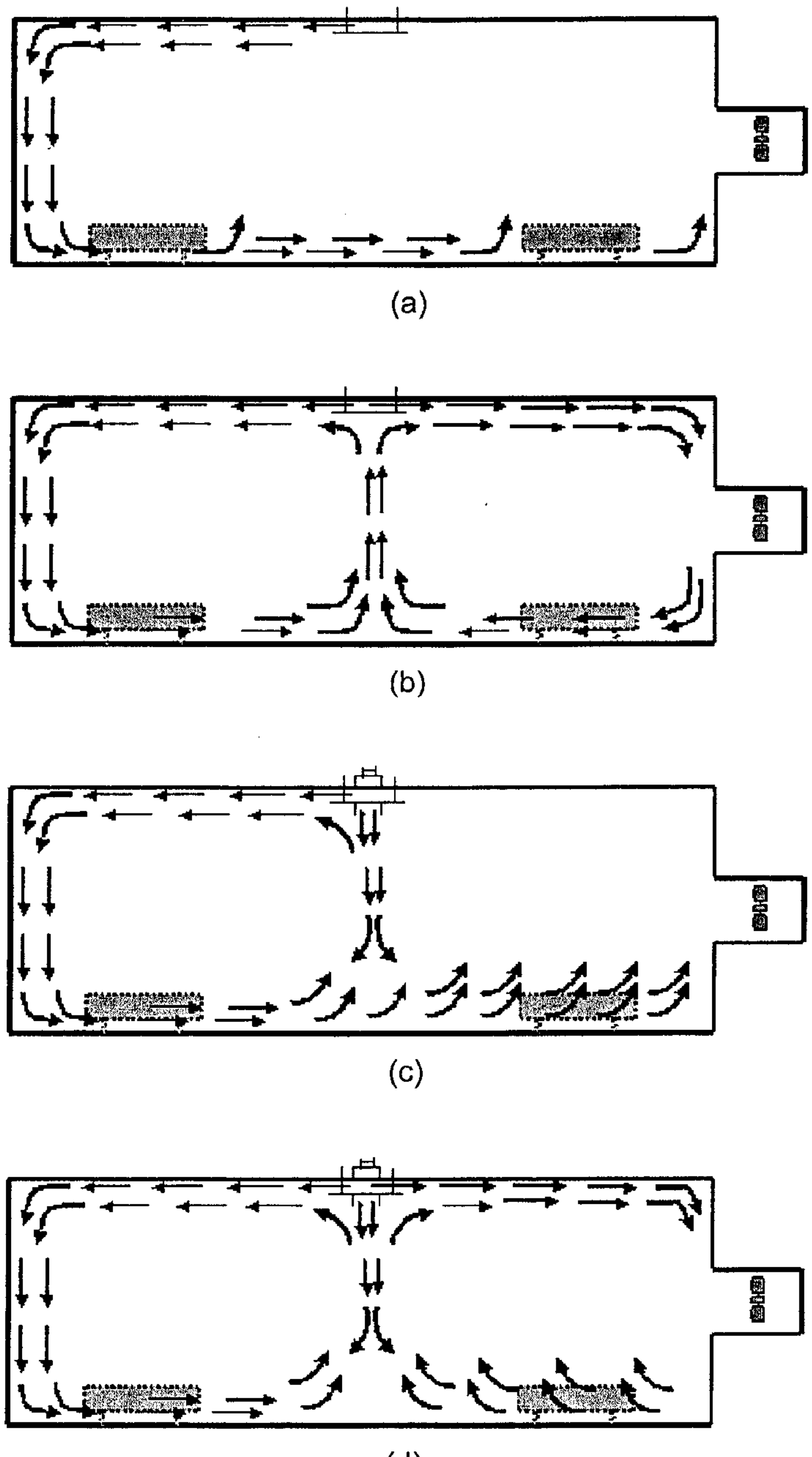


Figure 10. General airflow patterns for the different air inlets: (a) box1, (b) box2, (c) local1, and (d) local2. Arrow lengths do not represent the relative magnitude of the air velocities.

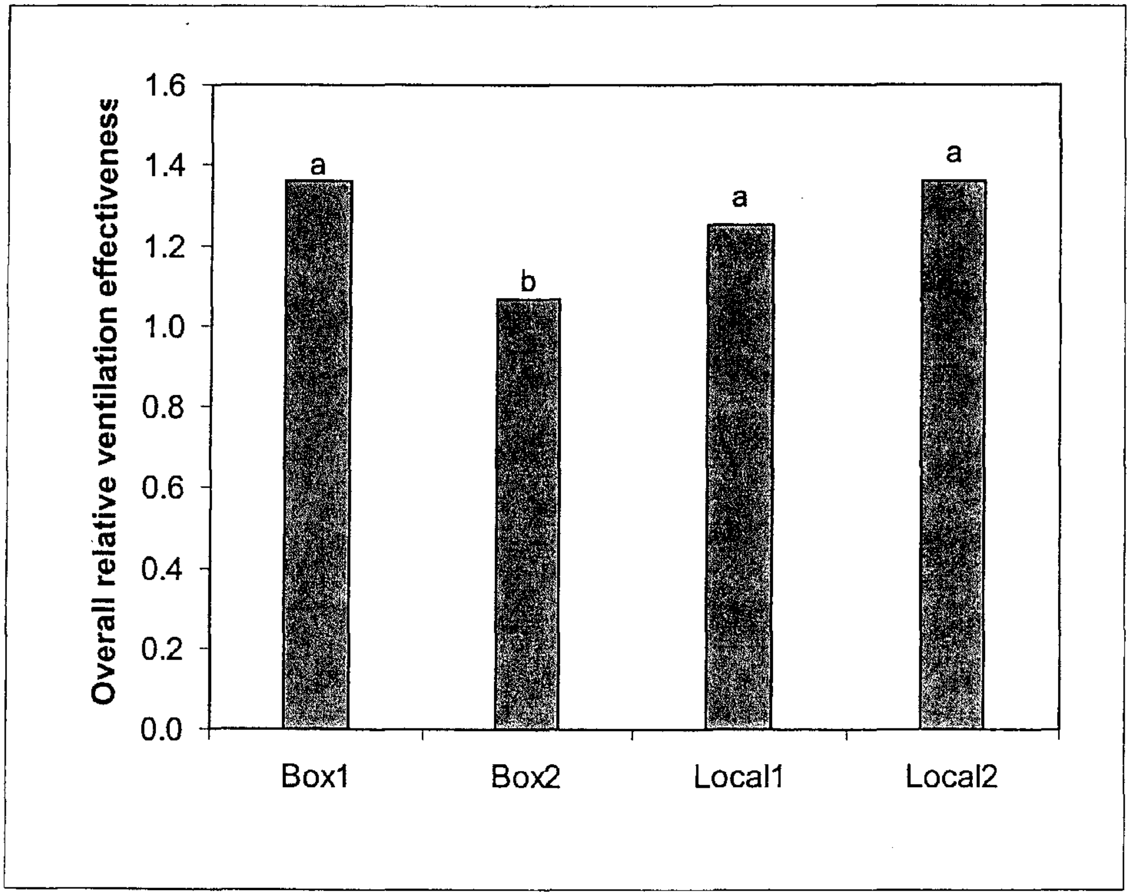


Figure 11. Overall relative ventilation effectiveness for the air inlets. Means with a common letter are not significantly different at the 5% level.

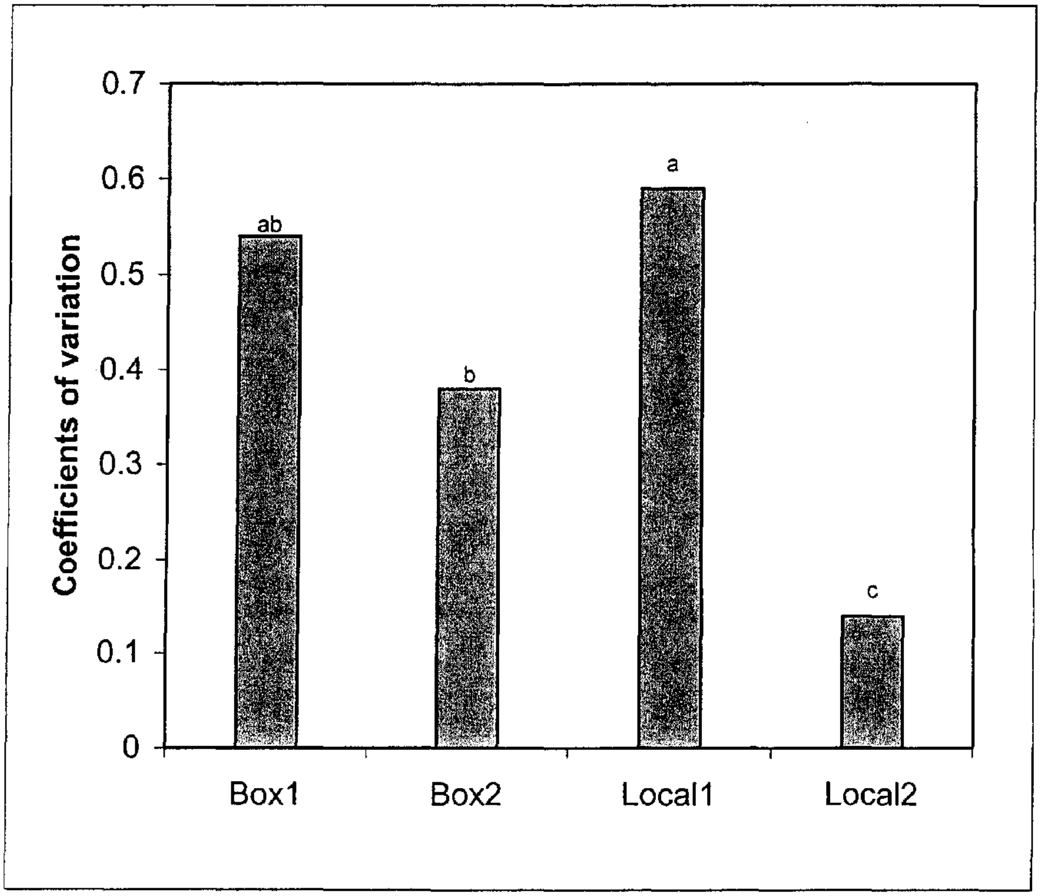


Figure 12. Coefficients of variation (CV's) of the dust concentrations for the four inlets. Means with a common letter are not significantly different at the 5% level.

Local1 ventilation system. Mean E_p was 2.76 for pens 1 and 2, 0.66 for pens 3 and 4, and 1.97 for the alley (fig. 9). Mean E_p's for pens 1 and 2 and the alley were not significantly different ($p>0.05$) from each other but were significantly ($p<0.05$) higher than that of pens 3 and 4. Differences can be explained in part by the prevailing air movement for this system (fig. 10c). The fresh supply air in the central alley mixed with the incoming air from the box-type air inlet resulting in a counterclockwise flow zone near pens 1 and 2. The supply air to the alley limited the transport of dust to the central alley but it also could have influenced the transport of dust to pens 3 and 4. The mean E_o and mean CV of the dust concentration for this system were 1.25 and 0.59, respectively (figs. 11 and 12). The lack of fresh supply air to pens 3 and 4 contributed to non-uniform mixing conditions in the room, resulting in relatively high CV.

Local2 ventilation system. Mean E_p was 1.60 for pens 1 and 2, 1.38 for pens 3 and 4, and 1.18 for the alley (fig. 9). Similar to the box1 and box2 air inlets, pens 1 and 2 had the highest mean E_p while the alley had the lowest mean E_p. Mean E_p's for pens 1 and 2 and pens 3 and 4 did not significantly differ ($p>0.05$). In addition, the mean E_p for the alley was not significantly different ($p>0.05$) from that of pens 3 and 4 ($p>0.05$). As noted for the box2 air inlet, the air movement in the room was dominated by two counter-acting circulation zones, which were nearly symmetrical about the central alley (fig. 10d). The airflow pattern shows that the incoming air descended both sidewalls and flowed inward across the pens. The supply air flowing in the alley did not strongly influence the incoming air, instead it mixed with the incoming air, ascended, and was entrained by the two ceiling jets. This prevailing airflow pattern resulted in the lower mean E_p in the alley than in the pens. For this system, mean E_o was 1.36 and mean CV of the dust concentration was 0.17 (figs. 11 and 12). This low CV suggests that the fresh supply air in the alley contributed to better mixing within the room.

Comparison of the ventilation systems. The type of ventilation system or supply air inlet significantly affected mean E_p for each sampling location (fig. 13). For pens 1 and 2, the box1 air inlet and the local1 system had the highest mean E_p; local2 had the lowest mean E_p, which did not significantly differ ($p>0.05$) from that of the box2 air inlet. For pens 3 and 4, the local1 system had the lowest mean E_p while the other three systems did not significantly differ ($p>0.05$). For the alley, the local1 system had the highest

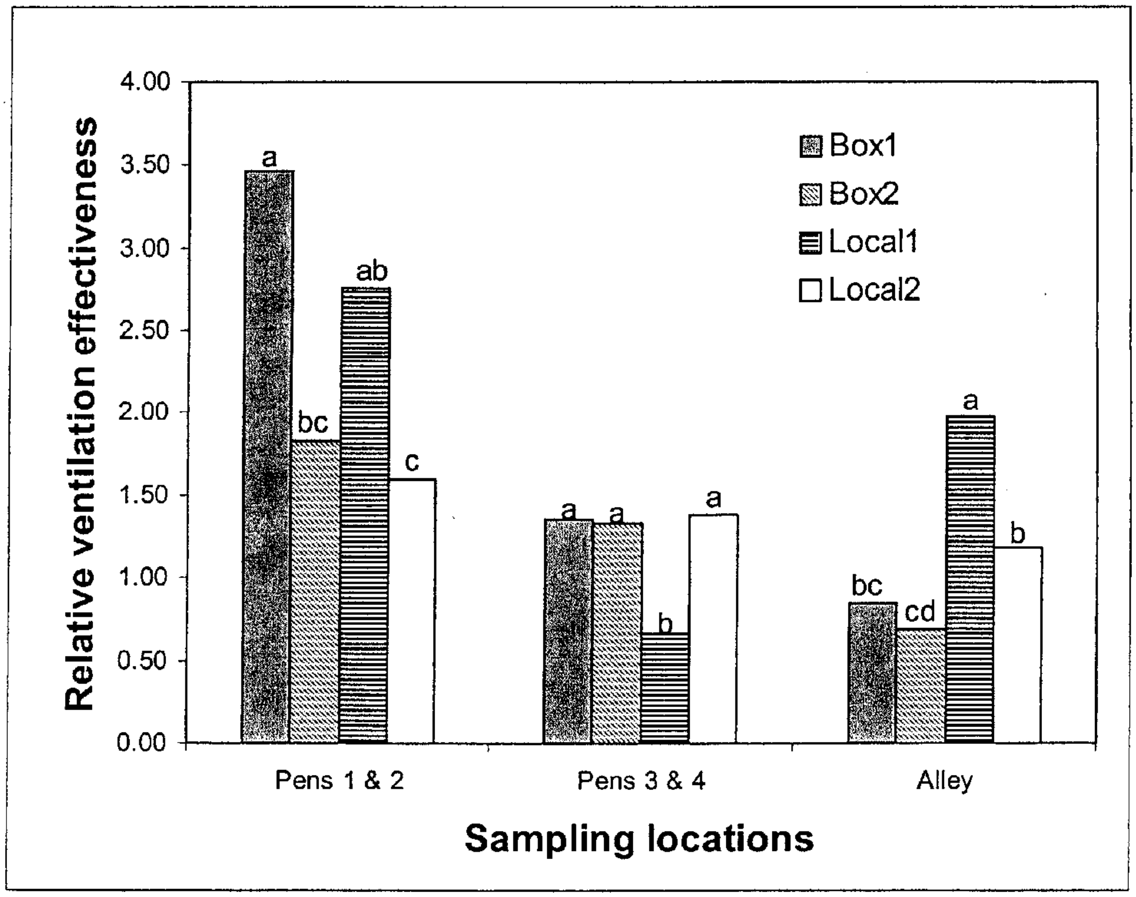


Figure 13. Relative ventilation effectiveness for each sampling location and for each air inlet. Means with a common letter within each sampling location are not significantly different at the 5% level.

mean E_p, followed by the local2 system. The box2 air inlet had significantly ($p<0.05$) lower E_o than the other three systems; the box1 air inlet and the two local systems did not differ ($p>0.05$) in overall E_o (fig. 11). The local2 system had the lowest CV or the most uniform dust concentration distribution; the local1 and box2 air inlets had the highest CV (fig. 12).

The local1 and local2 systems are designed expressly to introduce fresh air down the alley to the workers' breathing zone. Comparing E_p in the alley for box1 and local1 and for box2 and local2 illustrates the success of the local supply system in achieving that goal. The local1 ventilation system performed significantly ($p<0.05$) better than the box1 air inlet at the alley (mean E_p of 1.97 vs 0.85). Likewise, the local2 system performed significantly ($p<0.05$) better than the box2 air inlet at the alley (mean E_p of 1.36 vs 1.07). These results suggest that bringing fresh air down the alley could improve the ventilation effectiveness at the alley significantly and possibly improve working conditions for the workers.

Additionally, introducing fresh air to the alley either improved or maintained the overall ventilation effectiveness and air mixing. The box1 and local1 systems did not differ significantly ($p>0.05$) in terms of E_o and CV; however, the local2 system performed significantly ($p<0.05$) better than the box2 air inlet in terms of E_o and CV.

Effect of exhaust location. For the box2 air inlet, exhaust location had some effect on ventilation effectiveness and spatial variability in dust concentration. Exhaust location did not significantly ($p>0.05$) influence mean E_p for pens 1 and 2 and for the alley (figure 14). The wall exhaust had significantly higher E_o (1.07 vs 0.89; figure 8) and E_p for pens 3 and 4 (1.33 vs 0.76; figure 14) compared to the floor exhaust. However, it resulted in worse air mixing, as indicated by the higher CV (0.38 vs 0.23; figure 15).

For the local2 system, the wall exhaust was generally better than the floor exhaust as indicated by the higher E_o (1.36 vs 1.20), higher E_p for the alley (1.18 vs 0.70), and lower CV for dust concentration (0.17 vs 0.40).

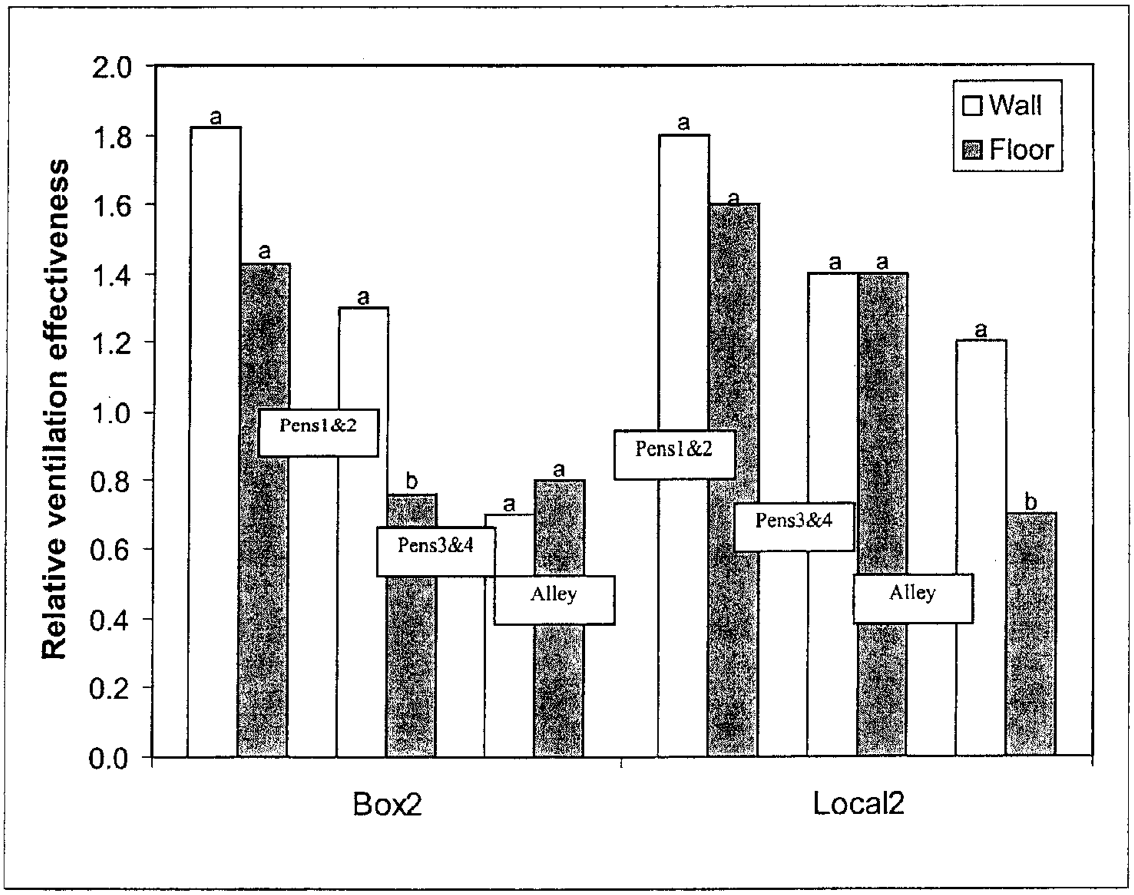


Figure 14. Relative ventilation effectiveness for exhaust locations within sampling location for box2 and local2 air inlets. Means with a common letter within each sampling location and exhaust location are not significantly different at the 5% level.

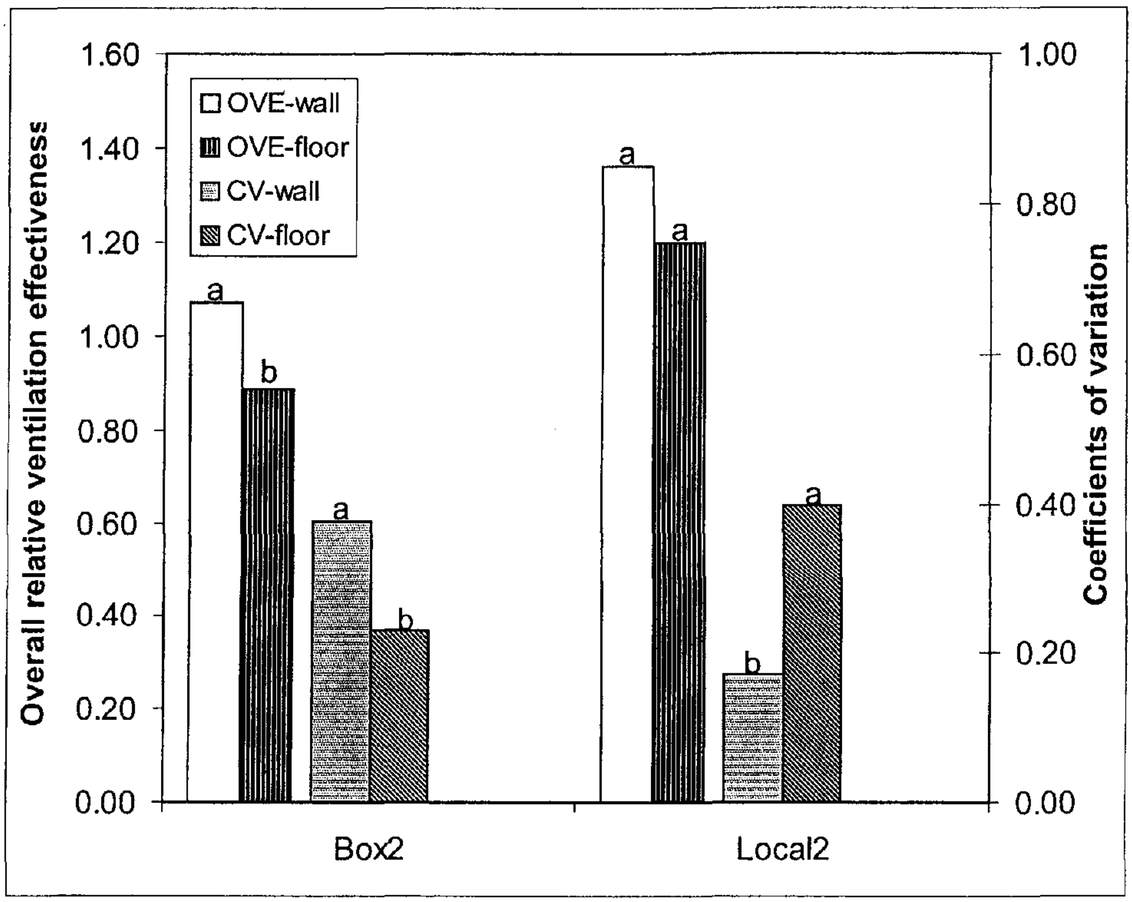


Figure 15. Overall relative ventilation effectiveness and coefficients of variation in dust concentration for each exhaust location for box2 and local2 air inlets. Means with a common letter within each exhaust location and air inlet type are not significantly different at the 5% level.

Conclusions

Study 2 compared the performance of conventional ceiling air inlets and local supply ventilation systems in terms of their relative ventilation effectiveness and spatial variability in dust concentration in an experimental facility. General findings are as follows:

- The type of air inlet or ventilation system significantly affected the ventilation effectiveness for airborne dust and spatial variability in dust concentrations.
- The local supply ventilation systems, in which supplemental air was introduced at the service alley, improved the ventilation effectiveness at the alley compared to the conventional air inlets. In addition, the local2 system had the highest overall relative ventilation effectiveness (E_o=1.36) and most uniform dust concentration distribution (CV=0.17).
- The wall exhaust was generally better than the floor exhaust, especially for the local ventilation system, in terms of ventilation effectiveness and spatial variability in dust concentration.

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3. Jerez, S.B. 2002. Experimental and numerical modeling of dust transport in a mechanically ventilated airspace. Unpublished M.S. thesis, Kansas State University, Manhattan, KS.

The first publication is a refereed journal article that presents the experimental results on the conventional supply air inlets (Study 1). The second is a manuscript based on the local supply ventilation system (Study 2); it has been submitted for publication in the *Transactions of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers*. The third is a M.S. thesis in Biological and Agricultural Engineering by Ms. Sheryll Jerez; it serves as a compilation of the first two papers and presents the results of the numerical simulation that was conducted to compliment the experimental work for this research project.