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Ventilation Design in Animal Research Facilities Using Static Microisolators

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ABSTRACT

This paper presents the key conclusions from an extensive research project on ventilation design in animal research facilities using static microisolators. This study, which is presented in full in Memarzadeh (1998), considered both experimental and numerical aspects using the computational fluid dynamics (CFD) technique. As well as a summary of various gaseous generation rates for mice, this paper contains conclusions on the effects of changing various parameters within an animal research room on conditions in the cages and in the main room volume itself. These parameters include, but are not limited to, supply type, exhaust location and number, room ventilation rate, and supply air temperature and moisture content.

INTRODUCTION

Optimum air quality in laboratory animal facilities is essential for the general health and well-being of researchers, animal caregivers, and the animals, as well as for the integrity of the studies. Since both genetic heritage and the environment influence biological responses, researchers must always be aware of the influence of the environment on the animals' biological responses. With more information about environmental effects, laboratory animal facility design and management can be improved. Researchers will obtain the most reliable and repeatable results from their studies and experiments when laboratory animals have the best possible environmental conditions.

Many thousands of square feet of animal research facilities are designed and constructed each year. Unfortunately, inadequate information is available regarding ventilation rates and patterns that are required to maintain acceptable micro (cage) and macro (room) environments. There is an immediate need for a definitive scientific basis for selecting the ventilation rates and for designing effective ventilation systems for laboratory animal facilities. Engineers need this information to design environments with good air quality and low energy usage.

Laboratory animal facility ventilation should balance air quality, animal comfort, and energy efficiency to provide cage environments that optimize animal welfare and research results. Conditions that optimize animal welfare minimize unintended stress factors that can significantly affect research results. Furthermore, researchers and animal caregivers have the right to expect a healthy and pleasant working environment.

A comprehensive study of air movement, heat transfer, and contamination dispersal in the macro- and microenvironment in animal facilities could only be undertaken using computational fluid dynamics (CFD). Apart from difficulties creating actual rooms with all the variations in layout and the ventilation schemes required, the control systems necessary to provide consistent conditions would be prohibitive. Even then the number of measurements required to fully document exactly what is happening in the room would be huge.

The use of CFD software enabled an extensive systematic study of the ventilation of animal facilities to be carried out. The CFD code chosen was produced by a company that specializes in software for the calculation of airflow, heat transfer, and contamination distribution in the built environment. The CFD software calculates the three-dimensional flow fields (air velocity, pressure, temperature, humidity, contaminant concentrations, etc.) at around one million points in the room and cages simultaneously. These data are then further post-processed, using analytical software to determine

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global factors (such as mean cage temperature and mean ammonia concentration), which are used to characterize the overall performance of the room.

BASE CASE ROOM

The general features of the room model were as follows.

Room:

- 6.10 m × 3.60 m × 4.22 m (20 ft × 12 ft × 9 ft)
- Door on short wall
- Sink in corner
- Laminar flow change station
- Five racks

Cages:

- Microisolator (with filter top) mouse cage
- Five mice per cage, 100 g (0.22 lb) total mice weight

Rack:

- Static system
- Six shelves per rack
- Seven cages per shelf (42 cages per rack)

Supply:

- Two radial supplies each providing 0.13 m^3/s (270 cfm) for a total of 15 ACH
- Supply discharge temperature, 18.8°C (66°F), set such that the exhaust air temperature was 22.2°C (72.0°F)
- Sixty-one percent relative humidity (to provide 50% RH at 22.2°C (72.0°F)

Exhausts:

- Two ceiling level exhausts removing 0.1 m^3/s (220 cfm) each

Makeup Air:

- 0.047 m^3/s (100 cfm) coming from around the door

Overall Geometry

In the cases considered here, the animal room occupied a floor area of 6.10 m (20 ft) × 3.66 m (12 ft). The ceiling height was 2.74 m (9 ft). There was only one door in the room, which was in the center of one of the short walls (see Figure 1).

In all the displacement ventilation systems considered in this project, air was introduced through ceiling-mounted diffusers. All devices were mounted flush with the ceiling surface; there was no ductwork present within the upper room volume. The various diffuser types considered in this project were all modeled using a combination of several boundary conditions, which were validated prior to the room parametric study (see Memarzadeh [1998]). All the air exited through general exhausts. The number and locations of the exhausts were varied. In line with common practice, there was an imbalance between the amount of air supplied to the room and the amount exhausted from the room. This leads to an overall pressurization of the room relative to the rooms or corridors surrounding the room. The makeup air to compensate for the supply/exhaust imbalance was allowed to enter or leave the room through 0.00635 m (0.25 in.) gaps on three sides of the door.

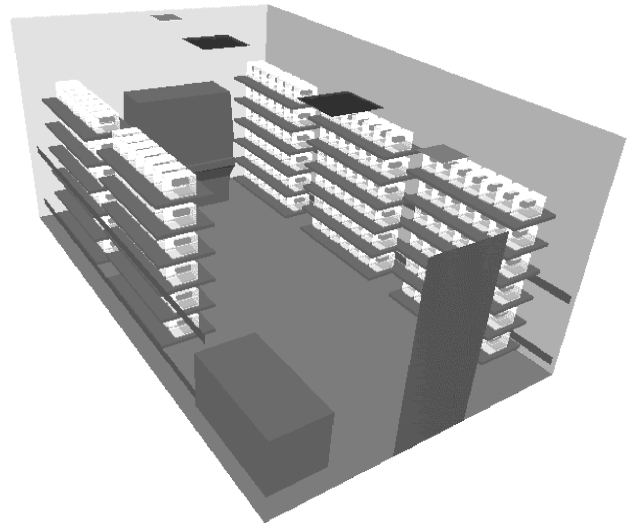

Figure 1 *Overall layout of animal room base case.*

The rooms considered in this study all contained five animal cage racks, as well as a typical change station. The only other item within the room was a sink of dimensions 0.61 m (24 in.) × 0.61 m (24 in.) × 0.81 m (32 in.) located in one of the corners of the room.

Rack Model

The overall dimensions of the rack were 1.52 m (60 in.) × 0.61 m (24 in.) × 1.83 m (72 in.) high. There were six shelves in the rack. The spacing of the shelves was 0.32 m (12.75 in.) from top surface to top surface. The lowest shelf was at a height of 0.21 m (8.25 in.) above the floor. The shelves were modeled as thin rectangular blocks. Details such as the connecting ties between the shelves and the rollers on which the racks move were not modeled, as their effect on the overall flow field and gas concentration distributions was considered insignificant.

Located on the shelves of the racks were computer model representations of the animal cages. The dimensions of the cage were 0.27 m (10.7 in.) × 0.16 m (6.38 in.) × 0.21 m (8.39 in.) high, which maintained the volume of the original cage that had sloped sides. The sides of the cage were modeled as thin plates, with the thickness and conductivity of the plates set to those of the physical cage polycarbonate. The water bottle and food normally found in a cage were modeled as a single block in order to reduce the computational overhead. The volume of the block was the same as that of the bottle and food combined. The bedding of the cage was included as a rectangular block of dimensions 0.27 m (10.7 in.) × 0.16 m (6.38 in.) × 0.0127 m (0.5 in.).

The spacing of the cages on the shelves was dependent on whether the racks were single density (seven cages per shelf) or double density (fourteen cages per shelf). In the single-density cases, the cages were centrally located in the short dimension and equally spaced in the long dimension. The spacing was 0.0488 m (1.92 in.) from a corner of the cage to a corner of the adjacent cage. In the double-density racks, the cages were equally spaced in both the long and short dimensions. The spacing was 0.022 m (0.87 in.) and 0.0488 m (1.92 in.), respectively.

Cage Characteristics

To ensure the computer models contain an accurate representation of the cage, it is necessary to specify pressure loss coefficients for the small gaps that exist around the cage where the top meets the bottom, as well as for the filter material in the lid of the shoebox cage. As most of the required data were not available from the literature, an unprecedented set of experimental measurements was undertaken. Without this foundation of accurate experimental data, the CFD analysis of the rooms would have had limited value.

Although some data exist on the flow resistance of filter material, determining how air gets in and out of the cages was vital for this study. The ventilation performance of a specific filter top microisolator cage was quantitatively measured for different airflow conditions. Of particular interest was the airflow between the upper and lower moldings, taking into consideration leakage that occurs because the top sits loosely on the bottom, compared with the ventilation through the filter top itself. A wind tunnel was designed, and in addition to tests on a single cage, tests were performed to measure the ventilation of two cages standing next to one another, closely representing a cage sitting on a rack in an animal facility room. CFD models of a cage in the wind tunnel, various orientations of a cage in the wind tunnel, and airflow velocities were constructed and run. These showed excellent agreement between the simulation results and the measured values, confirming that the cage model used in the room simulations was representative of a microisolator cage.

It was essential to include airflow in and out of the cages in the simulations in order to get a true representation of the interaction of the macro- and microenvironments. Figure 2 shows part of a typical airflow visualization, tracing the air that flows from two cages into the room. This air can be clearly seen to enter other cages some distance from the initial cages.

Change Station Model

The internal structure and flow field within the change station were of no concern in this study. It was only the effect of the station on the room airflow that was of importance.

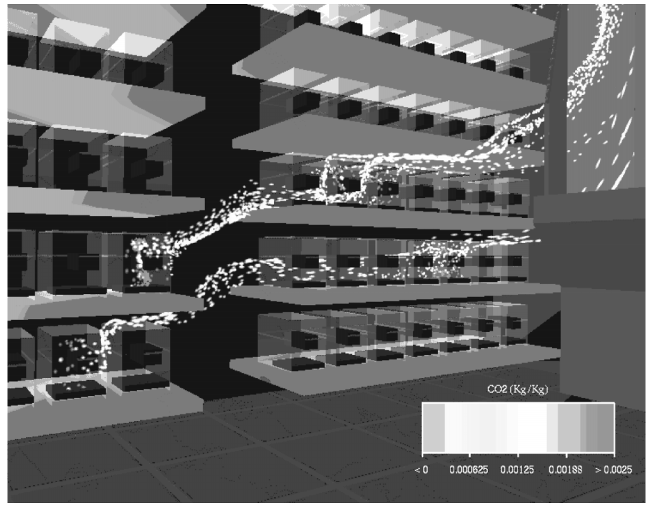

Figure 2 *Cage cross-contamination shown in a CFD flow visualization.*

Two designs were considered in this study, based on stations produced by different manufacturers. The first change station considered had overall dimensions of 1.32 m (52 in.) × 0.86 m (34 in.) × 1.83 m (72 in.). This design was effectively passive in terms of direct flow field interaction. In particular, the station internally recirculated a flow of 0.165 m^3/s (350 cfm) with only 10% leakage defined at the sash opening. The makeup air intake for this leakage was mounted at the side of the station. The station dissipated heat that was expected to affect the room's overall flow field. In particular, the station contributed a load of 720 W to the room. This heat was mostly confined to the lower portion of the station where the motor was located.

The second change station considered had overall dimensions of 1.50 m (59 in.) × 0.86 m (34 in.) × 1.93 m (76 in.) high. This station also recirculated air at 0.142 m^3/s (300 cfm) but discharged a much higher percentage than the first design. In particular, 0.0944 m^3/s (200 cfm) was discharged through grilles at the top of the station. The air makeup to compensate for this discharge was mounted at the front sill at the opening to the station. The station dissipated 660 W. This heat was considered to be added to the air discharge at the top of the station.

Modeling Assumptions

The following modeling assumptions were made:

- Solar load was not modeled through the walls of the room.
- The floor, ceiling, and walls were assumed to have no heat transfer, i.e., the surrounding areas were assumed to be at the same temperatures.
- All surfaces were treated as smooth when calculating surface friction.
- The sink in the animal room was modeled as a single rectangular block. The recess formed by the shape of the

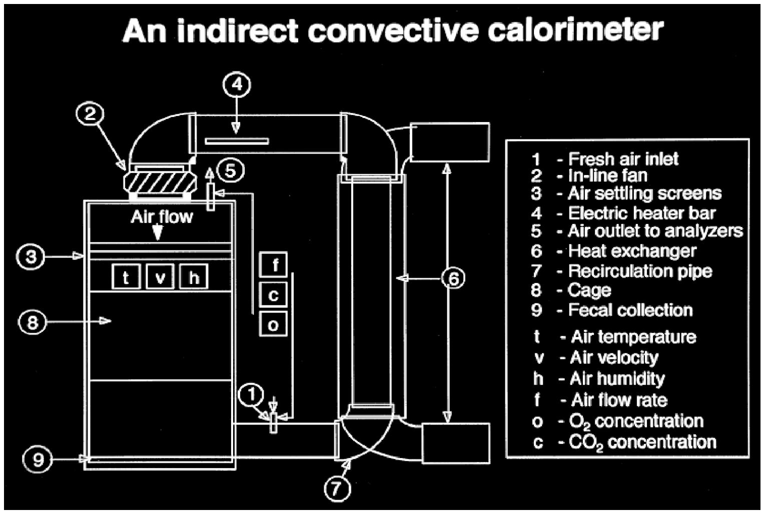

Figure 3 *Flow diagram—indirect convective calorimeter.*

sink was not modeled because the effect of the recess would be negligible on the overall flow field within the room.

- In all cases, the room was considered under scotophase conditions, i.e., the lights were off and produced no additional heat load. Dark period conditions were chosen because experimental studies for this project indicated that heat, CO_2, and NH_3 generations were higher in the scotophase compared with the photophase.
- The animal room was intended to be kept at a nominal 22.2°C (72.0°F). For the simulations, the temperature control was assumed to be placed in the exhausts, i.e., the exhaust air temperature was set to be 22.2°C (72.0°F), and the supply temperatures were set appropriately.
- No leakage occurred into or out of the animal room other than that specified though the cracks around the door.
- Air density variations due to temperature were negligible. Density variation was therefore ignored in all terms apart from in the momentum term for the vertical velocity component. This is known as the Boussinesq approximation (Flomerics 1994).
- The levels of CO_2 and NH_3 were so diluted in the whole room simulations, even at their source, that the variation of the mixture density due to differing molecular weights was negligible.

MICE CHARACTERISTICS

In addition to the normal CFD inputs of the geometry of the room and its contents, the behavior of the mice had to be defined for this study. This required data concerning heat dissipation and surface temperature of the mice, as well as moisture, CO_2, and NH_3 generation rates for mice. Defining these data required an extensive series of experimental measurements using sets of outbred female mice (HSD-ICR) with an initial age of four weeks.

The study was conducted at a major Midwest university and determined typical mass generation rates of CO_2, H_2O, and NH_3, consumption of O_2, and heat generation rates of mice in shoebox cages with bedding at two environmental relative humidities (35% and 75%). To determine the gas generation rates, the animals and their cage habitat were placed within enclosed chambers (open-system calorimeters, see Figure 3) with precisely controlled fresh air exchange rates. Cage bedding was not changed for longer than normal periods (10 days) to allow ammonia-generating bacteria to develop within the bedding, which allowed the taking of enough data to assess this time-dependent process.

On compilation of the results, it was demonstrated that the generation rates of both CO_2 and H_2O can be considered constant over the duration of the 10-day experiments. This conclusion is demonstrated graphically for CO_2 in Figure 4, which shows the scotophase CO_2 generation rate vs. day of experiment for the desired RH = 75%-80% tests. The equivalent plot for H_2O is very similar.

However, the generation rate of NH_3 is seen to depend on both the level of RH and the day of experiment. Figure 5 displays the NH_3 generation rate vs. day of experiment for desired RH = 30%-35% and 75%-80%. The plot shows a clear increase in the NH_3 generation rate with an increase in RH and day of experiment. It should be noted that the average level of cage RH achieved in the desired 30%-35% RH experiments was 61% (compared with the environmental RH average of around 39%), while the average level of cage RH in the desired 75%-80% RH experiments was 80%. For the purposes of interpolation, therefore, the values are only wholly accurate between 61% and 80% cage RH. While the NH_3 generation rate is clearly dependent on the RH in the cage, this is not the case for temperature. In particular, in Figure 6, which shows

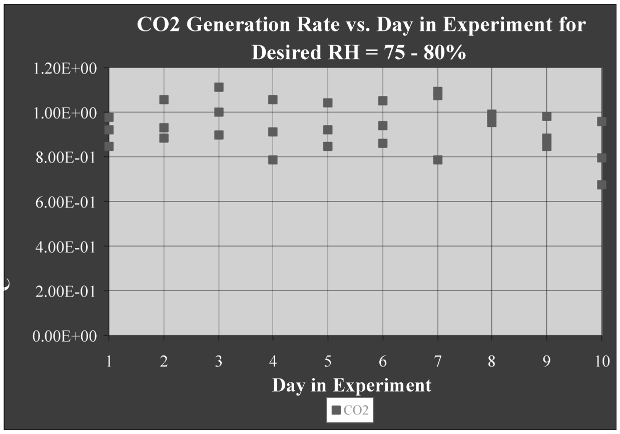

Figure 4 *Variation of scotophase CO_2 generation rate with day in experiment: desired RH = 75%–80%.*

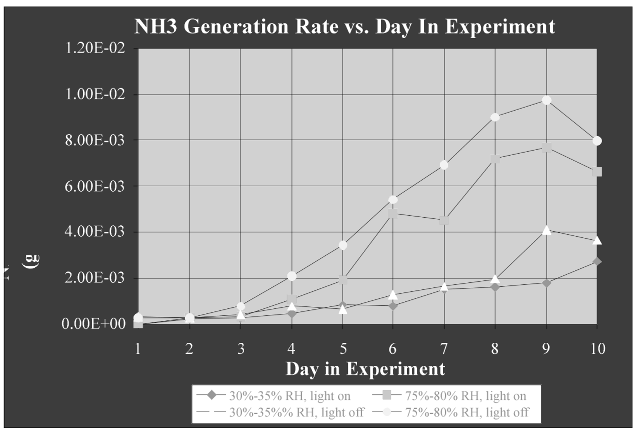

Figure 5 *Effect of photoperiod on gaseous exchange between the mouse cage and the room environment.*

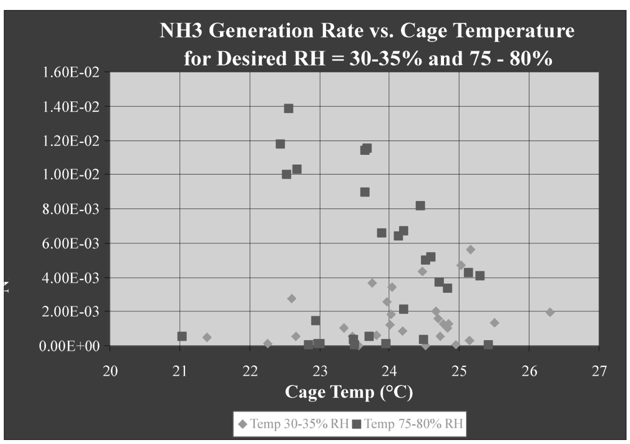

Figure 6 *Variation of scotophase NH_3 generation rate with cage temperature.*

the collection of the scotophase NH_3 generation rate vs. cage temperature for desired RH = 30%-35% and 75%-80% data for all the days in the experiment, there is no clear relationship between the generation rate and cage temperature.

Combining the data from both tests, average values were obtained. The average mass generation rates of CO_2 and H_2O, the average consumption rates of heat for the scotophase and photophase from both the experimental tests, are tabulated in Table 1. The NH_3 data cannot be averaged as constant values because of the dependence on cage RH, light phase, and day of experiment.

The averaged data clearly show that, for all measured values, the scotophase condition leads to higher generation/ consumption rates than the photophase.

The mice were modeled as a block of dimensions 0.11m (4.25 in.) × 0.0857 m (3.38 in.) × 0.22 m (0.88 in.). This was the same representation as was used in experimental cage wind tunnel tests (see Memarzadeh 1998), which were used to define the CFD cage model and simulated the effect of “huddling” by the mice. The surface temperature of the block was fixed at 30.0°C (86.0°F), which was agreed to be a typical mouse body surface temperature.

Surrounding this block was a source of contaminant that allowed the additional concentration of CO_2 and NH_3 in the air to be calculated in the simulation. The room supply air was assumed to have a zero concentration of CO_2 and NH_3. This means that all CFD results quoted are relative to the background level. If an absolute value for CO_2 is required, an additional amount in the range of 300 ppm to 700 ppm for most locations should be added.

The concentrations of NH_3 in both the cages and the room were also derived by scaling the concentration with a factor specified in the post-processing of the data. This factor (see above) was assumed to vary according to two variables: the number of days that passed since the bedding in the cage was changed and the average relative humidity in the cages.

TABLE 1
Average Gas Mass Generation/Consumption Rates and Average Generation Rates of Heat for the Scotophase and Photophase from All Experimental Tests

Variable	Scotophase	Photophase
CO^2 (g/h/100g bw)	0.905	0.692
CO^2 (ppm)	6147	4554
H^2O (g/h/100g bw)	0.831	
O^2 (g/h/100g bw)	0.660	0.575
Heat (W/100g bw)	2.69	2.40

ROOM VARIATIONS: THE RESULTS OF CFD SIMULATIONS

To investigate the relationships between room configuration parameters and the room and cage environments within laboratory animal research facilities, the following parameters were varied:

- Supply air diffuser type and orientation and air temperature and moisture content
- Room ventilation rate
- Exhaust location and number
- Room pressurization
- Rack layout and cage density
- Change station location, design, and status
- Leakage between the lower and upper cage moldings
- Room width

Room pressurization, change station design, and room width were found to have little effect on ventilation performance. However, all the other factors were found to affect either or both of the macro- or microenvironments to a greater or lesser extent.

The key conclusions of this research are:

- Ammonia production rates depended on the relative humidity in the cages and the number of days that had elapsed since the bedding was changed. Figure 7 shows the data points measured and the best fit lines ("Poly") for the data. Five days after the last change of bedding, ammonia was produced in a high-humidity environment at approximately three times the rate as in a low-humidity environment. This research showed that the rate of ammonia generation was not directly dependent on temperature, although temperature has a direct effect on the relative humidity of the air.
- Acceptable room and cage ammonia concentrations after five days without changing cage bedding are produced by room supply airflow rates of about 0.0004 m^3/s (0.85 cfm) per 100 g of body weight of mice. This is equivalent to 5 ACH for rooms with 210 cage racks, which were considered in this study, and 10 ACH for rooms with 420 cages. This indicates that it could be possible to adjust the common practice of changing bedding every four days to changing after five days.

The temperature of the supply air must be set appropriately for the heat load in the room. In this study, the change station produced 720 W and the mice around 500 W in the single-density racks, which required supply discharge temperatures of 11°C (52°F) at 5 ACH to provide exhaust temperatures of around 22°C (72°F). For double-density racks, the supply discharge temperature should be 14.8°C (59°F) at 10 ACH.

This study used dark period/lights off to give the highest CO_2 and NH_3 generation rates. If lighting is to be included, an allowance should be made for 600 W of additional heat from the lights, leading to lower supply discharge temperatures.

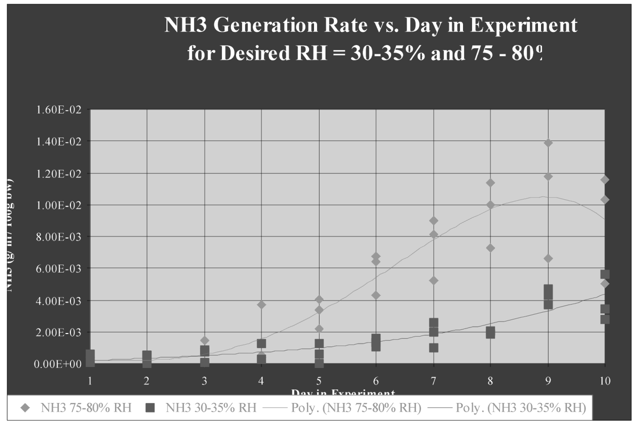

Figure 7 *Ammonia generation rate measured over 10 days at high and low humidity.*

- Increasing the room ventilation rate for a given design appears to have a beneficial effect on the room's breathing zone ventilation as measured by CO_2 and ammonia concentrations. For the single-density racks (210 cages) parallel to the walls, increasing the supply flow rate from 5 ACH to 20 ACH reduced the breathing zone CO_2 concentration from 140 ppm to 63 ppm. This is a decrease of 55%. For the double-density racks perpendicular to the walls, the reduction is even more dramatic. A reduction of over 70%, from more than 300 ppm to 93 ppm, occurred when the flow rate was increased from 5 ACH to 20 ACH.

However, the "high" values of CO_2 concentration of about 300 ppm above the background levels are still very low. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a threshold limit value (TLV), time-weighted average (TWA) of 5000 ppm (9000 mg/m^3) for carbon dioxide. ACGIH also recommended a short-term exposure limit (STEL) of 30,000 ppm (54,000 mg/m^3).

Although 20 ACH appears to produce the best ventilation for the low induction diffuser with low-level exhaust cases, over 50% of the 15 ACH runs with other diffusers; exhaust locations or rack layouts actually have even lower room CO_2 concentrations.

Higher supply discharge airflow rates are usually accompanied by higher supply discharge temperatures since the air does not have to be so cold to extract the heat generated in the room. This allows animal facility designers/operators to choose between using low supply volumes at lower supply temperatures, with a lower cost for fans but higher cost for air conditioning, or high flow rates at higher temperatures, which result in higher fan but lower air-conditioning costs. Which of these options will provide the best economic return depends on the facility's circumstances.

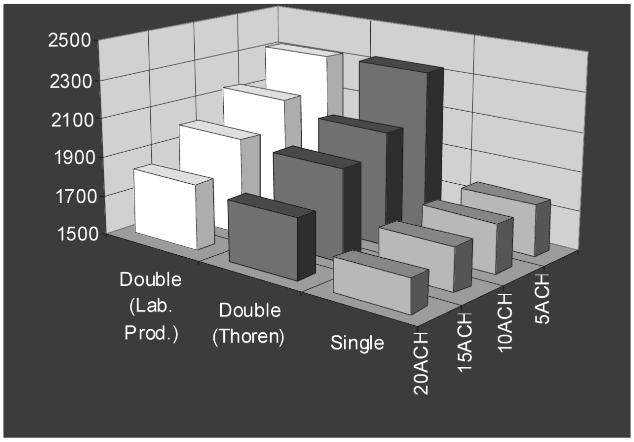

Figure 8 *Cage CO_2 concentrations (ppm) for single-density racks with the first change station design considered and double-density racks with both first and second change station designs considered.*

- Increasing the room ventilation rate does not have a significant effect on cage ventilation (see Figure 8). Increasing the supply flow rate from 5 ACH to 20 ACH for single-density racks parallel to the walls reduces the CO_2 concentration from 1764 ppm to 1667 ppm, a reduction of only 6%. For the double-density racks perpendicular to the walls, the reduction is slightly more significant—about 2300 ppm to 1800 ppm, or roughly 20%.

Since air exchange rates in excess of 10 ACH do not materially improve environmental conditions within the cages, more care should be given to proper cage arrangement and air distribution.

- Ammonia concentrations in both cages and rooms can be reduced by increasing the supply air temperatures. This reduces the relative humidity (RH) for a constant moisture content in the air. In addition, the lower RH leads to lower ammonia generation. Raising the supply discharge temperature from 18.8°C (66°F) to 22°C (72°F) at 15 ACH raises the room temperature by 3°C (5°F) to about 23°C (73°F) and the cages by 2.7°C (4°F) to around 24°C (77°F). This can reduce ammonia concentrations by up to 50%.

Using 22°C (72°F) as the supply discharge temperature at 5 ACH, which is the lowest flow rate considered, for double-density racks produces a room temperature of about 26°C (79°F) with cage temperatures only slightly higher. Although this higher temperature provides a more comfortable environment for the mice (Gordon et al. 1997), the high room temperature may be uncomfortable for the scientists and animal caregivers working in the room.

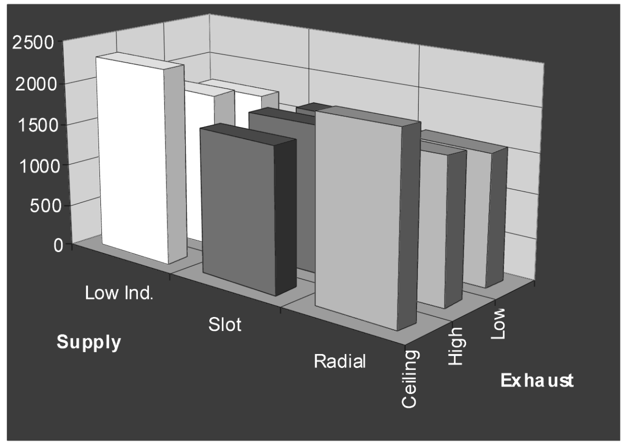

Figure 9 *Mean CO_2 concentration (ppm) in cages for radial, slot, and low induction supply diffusers with ceiling, high-level, and low-level exhausts.*

- Ceiling or high-level exhausts tend to produce lower room temperatures when compared to low-level exhausts. All CFD models were designed to have 22°C (72°F) for a given supply air temperature at the room exhausts. There were also a small number of tests run with high supply temperatures. These studies indicate that low-level exhausts are less efficient at cooling the room and will be more expensive to operate.
- Low-level exhausts appear to ventilate the cages slightly better than ceiling or high-level exhausts when the cages are placed parallel to the walls. Improvement was up to 27% for the radial diffuser, 4% for the slot diffuser, and 25% for the low induction diffuser (see Figure 9). The ammonia concentration in the cages (see Figure 10) appears to be even further reduced, although this is due to the higher temperatures in the low-level exhaust cases when compared to the ceiling and high-level exhausts, which act to reduce the relative humidity and the ammonia generation rate.

The room concentrations of CO_2 and ammonia do not show any supply or exhaust type to be significantly better or worse than any other type (see Figures 11 and 12). Of the many supply diffuser and exhaust locations considered in this work, it is not possible to select one configuration that will always perform better than another. Designers and operators of animal facilities will need to consider carefully which parameters are important to them and select a layout that balances all their requirements for animals and the humans that work with them.

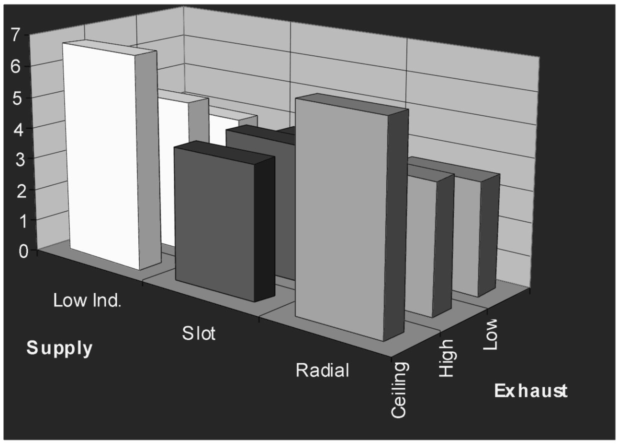

Figure 10 *Day 4 mean ammonia concentration (ppm) in cages for radial, slot, and low induction supply diffusers with ceiling, high-level, and low-level exhausts.*

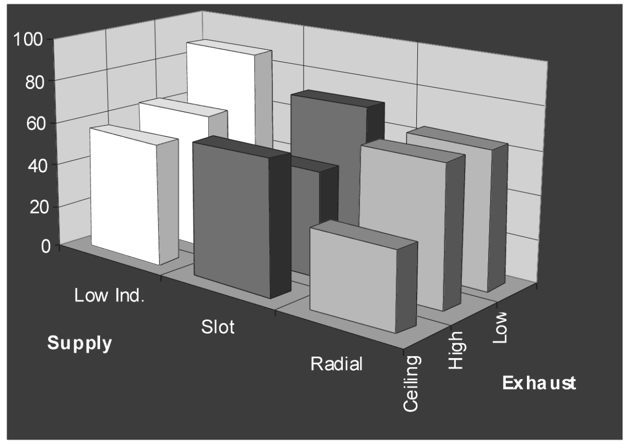

Figure 11 *Mean CO_2 concentration (ppm) in room breathing zone for radial, slot, and low induction supply diffusers with ceiling, high-level, and low-level exhausts.*

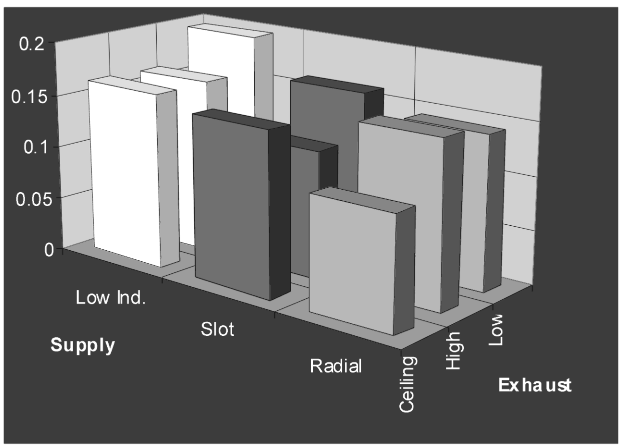

Figure 12 *Mean day 4 ammonia concentration (ppm) in room breathing zone for radial, slot, and low induction supply diffusers with ceiling, high-level, and low-level exhausts.*

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