DA-00-14-3

Analysis of Air Supply Type and Exhaust Location in Laboratory Animal Research Facilities Using CFD

Andrew Manning, Ph.D.

Farhad Memarzadeh, Ph.D., P.E.

Gerald L. Riskowski, Ph.D., P.E.
Member ASHRAE

ABSTRACT

The results from a computational fluid dynamics (CFD) study on the effect of air supply diffuser type and exhaust location in a typical animal research laboratory are presented. The results show that low-level exhausts produce higher temperatures in the room and cages, but the best in-cage ventilation (lowest CO_2 concentrations) compared with ceiling or high-level exhausts. Further, the study shows that the slot diffuser seems least sensitive to exhaust position. Finally, the results show that the room concentrations of CO_2 and NH_3 do not show any supply type or exhaust location to be significantly better or worse than any other type.

INTRODUCTION

A study was made on the effect of air supply diffuser type and exhaust location in a typical animal research facility using the technique of computational fluid dynamics (CFD). This study was part of a major research program conducted by the National Institutes of Health in collaboration with a major Midwest university to produce a ventilation design handbook on rodent laboratory research facilities using static microisolators. The CFD code used was produced by a company that specializes in software for the calculation of airflow, heat transfer, and contamination distribution in building environments.

The three diffuser types were radial diffusers, slot diffusers, and low induction diffusers. The three exhaust locations considered were ceiling (two grilles), high level (four grilles), and low level (four grilles).

Various physical properties were considered to assess the effects of the parametric changes. They were temperature, CO_2 concentrations, NH_3 concentrations, and relative humidity (RH). These properties were considered both in the cage and room.

OUTLINE OF CFD BASELINE MODEL

A typical animal research facility in terms of overall size, air change rate, rack layout, mouse population, room pressurization, and other characteristics was modeled as the baseline model for the CFD simulations. The general features of the room are shown in Figure 1 and listed below.

Description in Brief

The general features of the base-case room model were the following.

Room:

- 6.10 m long × 3.60 m wide × 4.22 m high (20 ft × 12 ft × 9 ft)

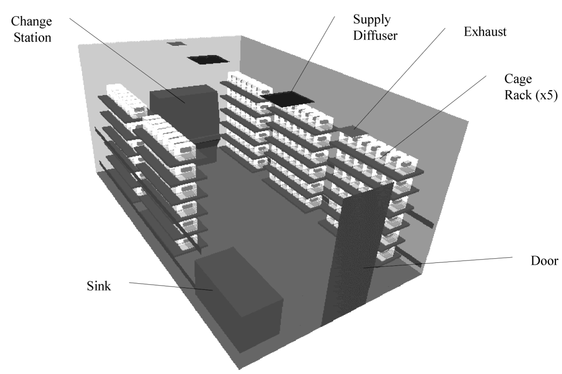

Figure 1 *Overall layout of animal room base case.*

Andrew Manning is BDD technical supervisor at Flomerics, Inc., Marlborough, Mass. **Farhad Memarzadeh** is chief of the Technical Resource Group, National Institutes of Health, Bethesda, Md. **Gerald L. Riskowski** is a professor at the University of Illinois, Urbana, Ill.

- Door on short wall
- Sink in corner
- Laminar flow change station
- Five cage racks

Cages:

- Microisolator (with filter top) mouse cage
- Five mice per cage at 20 g/mouse (100 g total body weight per cage)

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 so 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 all the 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 below). 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 the bottom and two sides of the door.

The rooms considered in this study all contained five animal cage racks, as well as a typical change station. A fuller description of these items is given below. The only other item within the room was a sink of dimensions 0.61 m wide (24 in.) by 0.61 m deep (24 in.) by 0.81 m high (32 in.) located in one of the corners of the room.

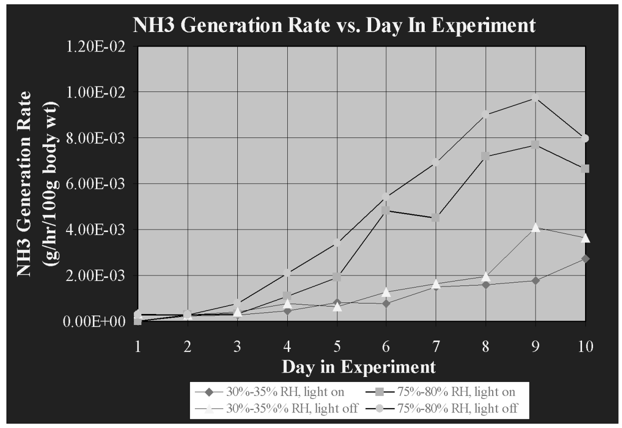

Figure 2 *Effect of photoperiod on gaseous ammonia exchange between the mouse cage and the room environment.*

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 early experimental studies for this project indicated that heat, CO_2, and NH_3 generations were higher in the scotophase compared with the photophase. Figure 2 shows the variation in NH_3 generation over a ten-day period. For CO_2 the generation in the light period was 0.68 (g/h)/100 g BW compared to 0.91 (g/h)/100g BW for the dark period.

Rack Model

The overall dimensions of the racks were 1.52 m (60 in.) long by 0.61 m (24 in.) deep by 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.) 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 representations of the animal cages. The dimensions of the cage were 0.27 m (10.7 in.) long by 0.16 m (6.38 in.) wide by 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 with dimensions of 0.27 m (10.7 in.) length by 0.16 m (6.38 in.) width by 0.0127 m (0.5 in.) height.

The mice were modeled as a block with dimensions of 0.11 m (4.25 in.) width by 0.0857 m (3.38 in.) length by 0.22 m (0.88 in.) height. This was the same representation as was used in experimental cage wind tunnel tests (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, a source of concentration was defined at 0.000000254 kg/s (0.91 g/h) for 100 g of mouse body weight in each cage, which was based on the generation rate obtained for the scotophase in tests on the effect of the photoperiod on the mice (Memarzadeh 1998). The definition of this source allowed the calculation of CO_2 in the room and cages. It also allowed the concentration of other gases, such as NH_3, to be calculated by scaling, even though it has a different molecular weight than both air and CO_2. This was possible because the magnitude of the source was very small and the resulting concentrations were so low as to have a negligible effect on the density of the mixture of air, CO_2,and NH_3. In effect, the CO_2 and NH_3 are intimately mixed with and flow with the air. The scaling factor for NH_3 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 (Memarzadeh 1998) for the experimental determination of the factors.

Background levels of CO_2 and NH_3 were assumed to be zero. This means that all values quoted in the CFD section of the report 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 remaining cage boundary conditions are associated with the transfer mechanisms for air/gases to enter/leave the cage. The cracks at the side of the cage and the top of the cage, which was filtered, were defined using CFD boundary conditions best suited to model them. The actual specification of the boundary conditions was achieved through extensive validation of the CFD cage model against experimental data obtained during this project (Memarzadeh 1998). This phase of work was very important, as it ensured that values for CO_2, NH_3, etc., obtained by the CFD simulation were accurate and also that transfer of air and concentration between the room and the cages and between cages themselves were correctly simulated.

The spacing of the cages on the shelves was dependent on whether the racks were single density (7 cages per shelf) or double density (14 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 corner of cage to corner of 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.

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.

The design considered in this study is based on a change station produced by a major manufacturer. The station had overall dimensions of 1.32 m (52 in.) width by 0.86 m (34 in.) depth by 1.83 m (72 in.) height. 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.

CFD MODEL VALIDATION

A series of validation exercises were performed during this study to ensure that the CFD models used to represent the critical physical items in the room—for example, the cages, diffusers, etc.—were accurate. The diffuser validation will be presented here. (The validation of the CFD cage model is too lengthy to be included here; a full description of the cage model validation is included in Memarzadeh [1998]). During this study, three different diffuser types were studied: radial diffuser, slot diffuser, and low induction diffuser.

Radial Diffuser

This diffuser is so named because it is designed to provide an airflow pattern that spreads in a fan-shaped (or radial) fashion perpendicular to the centerline of the diffuser. The intention of this is to prevent the formation of recirculation zones on either side of the diffuser that could potentially retain contaminants. For this reason, this type of diffuser/flow pattern has become increasingly popular in animal rooms and was chosen for the base-case whole room simulation. It was also used in the empty and populated room experimental scenarios. It should be noted, however, that the sideways throw characteristics could be compromised when strong thermal effects are present.

The manufacturer's test facility for this diffuser was 3.66 m (12 ft) long, 3.66 m (12 ft) wide, and 2.74 m (9 ft) high. The diffuser is located centrally in the ceiling of the test room. Two 0.30 m (1 ft) high exhausts are located at floor level. The manufacturer's data listed the vertical and horizontal distance of the 0.25 m/s (50 fpm) throw isovel (line of constant velocity) from the diffuser that was used in the validation exercise for various flow rates.

The CFD representation of the test facility took advantage of symmetry: the right side of Figure 3 represents the symmetry plane. The flow rate chosen from the manufacturer's data for validation purposes was that nearest the base-case flow rate through a single radial diffuser. Specifically, the base-case

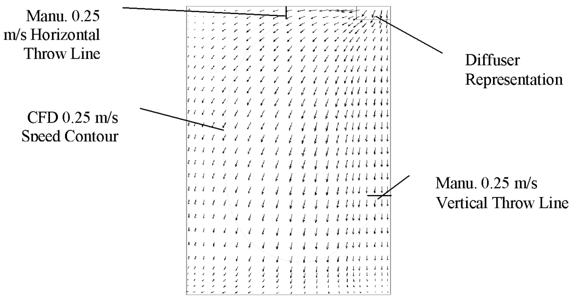

Figure 3 *Comparison of CFD and manufacturer's data for radial diffuser.*

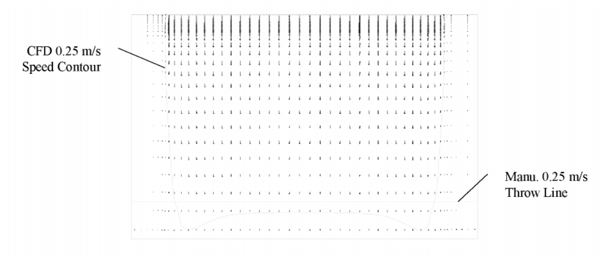

Figure 4 *Comparison of CFD and manufacturer's data for slot diffuser.*

flow rate was 1.35 m/s (270 cfm), while the nearest manufacturer's data point is for 1.5 m/s (300 cfm). Further, the effect of temperature was also considered. The data point chosen was for a 2.8°C (5.0°F) rise in the air temperature between the discharge and the exhaust. Heat sources were applied to the walls of the CFD model to provide such a temperature rise.

Figure 3 indicates that the CFD representation of the radial diffuser matches the location of the vertical and horizontal 0.25 m/s (50 fpm) isovel data very well. Therefore, confidence can be placed in the representation of the CFD radial diffuser in the animal facility simulations.

Slot Diffuser

The slot diffuser provides high shear flow conditions at the inlet that result in high entrainment of the surrounding air into the jet flow and, consequently, highly mixed conditions.

The manufacturer's test facility in this instance measured 5 m × 7 m × 3 m high (16.4 ft × 22.97 ft × 9.84 ft). The diffuser was centrally located in the ceiling of the test room. The manufacturer's data listed the vertical distance of the 0.25 m/s (50 fpm) throw isovel from the diffuser that was used in the validation exercise for various flow rates.

In the CFD representation, the flow rate that was chosen from the manufacturer's data for validation purposes was that nearest the base-case flow rate through a single radial diffuser. Specifically, the base-case flow rate was 1.35 m/s (270 cfm), while the nearest manufacturer's data point was 1.75 m/s (350 cfm).

Figure 4 shows that the CFD representation of the slot diffuser matches the location of the 0.25 m/s (50 fpm) isovel data very well. Therefore, confidence can be placed in the representation of the CFD slot diffuser model in the animal facility simulations.

Low Induction Diffuser

The low induction diffuser provides low shear flow conditions at the inlet that result in low induction of the surrounding air into the jet flow. Therefore, this diffuser provides a solid column of clean air, purging the space of contaminants immediately below it. The disadvantage is then that large recirculations are formed on either side of the diffuser jet.

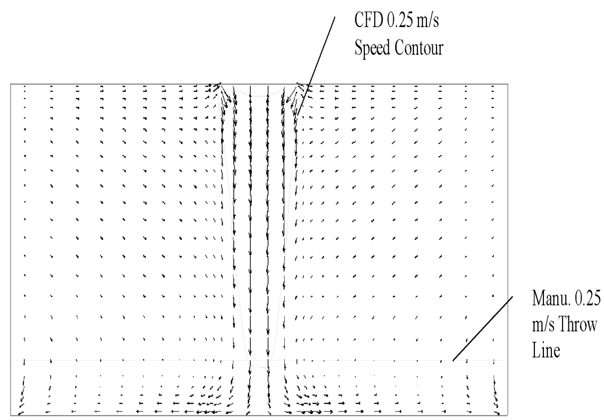

Figure 5 *Comparison of CFD and manufacturer's data for low induction diffuser.*

The manufacturer's test facility in this instance measured 5 m × 7 m × 3 m high (16.4 ft × 22.97 ft × 9.84 ft). The diffuser was centrally located in the ceiling of the test room. The manufacturer's data indicated the vertical distance of the 0.25 m/s (50 fpm) throw isovel from the diffuser that was used in the validation exercise for various flow rates.

In the CFD representation, the flow rate that was chosen from the manufacture's data for validation purposes was that nearest the base-case flow rate through a single radial diffuser. The base-case flow rate was 1.35 m/s (270 cfm), while the nearest manufacturer's data point was 1.625 m/s (325 cfm).

Figure 5 shows that the CFD representation of the low induction diffuser matches the location of the 0.25 m/s (50 fpm) isovel data very well. Confidence can, therefore, be placed in the representation of the CFD low induction diffuser model in the animal facility simulations.

PARAMETERS CONSIDERED

The following parameters were considered in this study:

- *Diffuser type*. All three diffusers listed above were considered, namely, radial diffusers, slot diffusers, and low induction diffusers.

TABLE 1
CFD Animal Room Cases Considered

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Status)	Rack Orientation	Rack Density	Makeup Air (m^3/s)/ Pressurization of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Base Case	Radial	Ceiling (x2)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 02	Radial	High (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 03	Radial	Low (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 04	Slot	Ceiling (x2)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 05	Slot	High (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 06	Slot	Low (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 07	Low Ind	Ceiling (x2)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 08	Low Ind	High (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15
Case 09	Low Ind	Low (x4)	ON	Parallel	Single	0.047/Neg.	18.8 (65.8)	15

- *Exhaust location*. Three different exhaust locations were considered: ceiling (two exhausts) and high (four exhausts) and low level (four exhausts).

Table 1 summarizes the nine cases considered in this study.

Various physical properties were considered to assess the effects of the parametric changes including temperature, CO_2 concentrations, NH_3 concentrations, and relative humidity (RH). These properties were considered both in the cage and room.

PARAMETRIC RESULTS

Cases 1 (the base case) to 3 had a radial diffuser supply with ceiling, high-level (on side walls, and low-level (on side walls) exhausts, respectively. Cases 4 to 6 used a slot diffuser, and cases 7 to 9, a low induction diffuser with the same exhaust configurations.

Figures 6 to 10 show three-dimensional bar charts comparing temperature, CO_2, NH_3, and relative humidity for both the cages and the breathing zone in the center of the room.

Figure 6 shows that the higher temperatures (by about 2°C [4°F]) produced in the cages in the low-level exhaust runs indicates this exhaust location is less efficient in cooling the room compared with the high-level and ceiling level exhausts. A similar conclusion can be drawn on examination of breathing room data.

The lower values of CO_2 concentration in the cages for the low-level exhaust (up to 27% for the radial diffuser, 4% for the slot diffuser, and 25% for the low induction diffuser) indicate that the cages are better ventilated in this situation. This is indicated in Figure 7. The room values show that the best ventilation of the room occurs with a radial diffuser and ceiling-level exhausts.

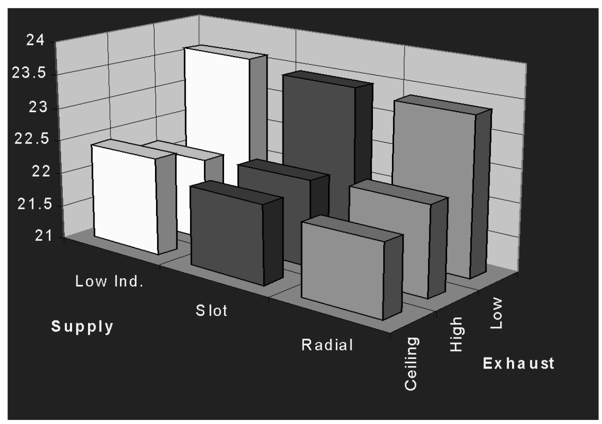

Figure 6 *Comparison of mean cage temperatures (°C).*

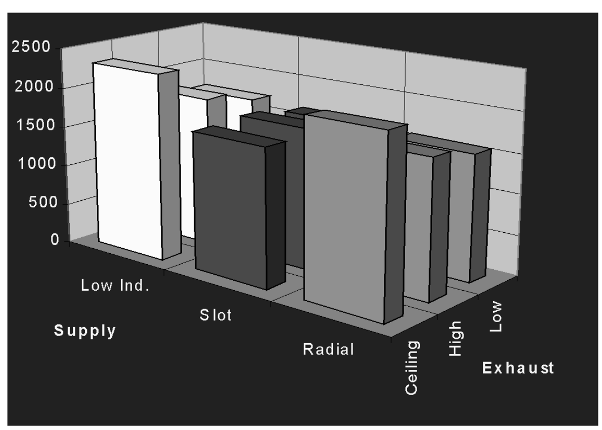

Figure 7 *Comparison of mean cage CO_2 concentration (ppm).*

Figures 8 and 9 show that the room and cage NH_3 concentrations show a pattern similar to the CO_2 concentrations. The variations are, however, somewhat larger, as the higher temperatures in the low-level exhaust cases reduce the relative humidity in the cages and reduce the rate of NH_3 generation, which leads to lower concentrations in the cages.

Lower relative humidities in the low-level exhaust cases are mainly due to the higher temperatures (Figure 10).

The low CO_2 concentrations seem to be due to the higher flow around the cages, and this extra flow clearly helps ventilate the cages.

The ceiling-level exhausts produce the lowest levels of CO_2 for the radial and low induction diffusers in the room's breathing zone. This appears to be caused by the main airflow going through the cages toward the side walls at this height, whereas in the other cases, more air is coming from the side walls into the central region. This can be seen in Figures 11 and 12, which show the distribution of CO_2 concentration for the radial diffuser and ceiling-level and low-level exhausts.

The slot diffuser seems least sensitive to exhaust position. This is probably due to the slot diffuser creating much higher entrainment and mixing due to the higher supply air velocity and increased jet area.

The increase in temperature from the lower room ventilation efficiency, apparent in both the cages and the room for the low-level exhausts, helps to keep the cage humidity levels low and reduces NH_3 production.

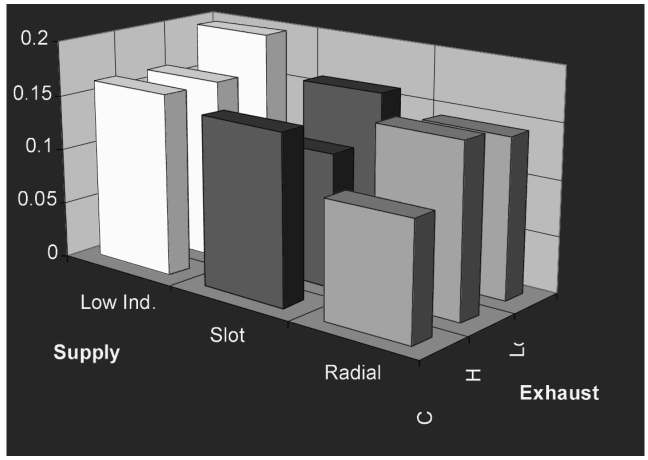

Figure 8 *Comparison of room breathing zone NH_3 concentration (ppm).*

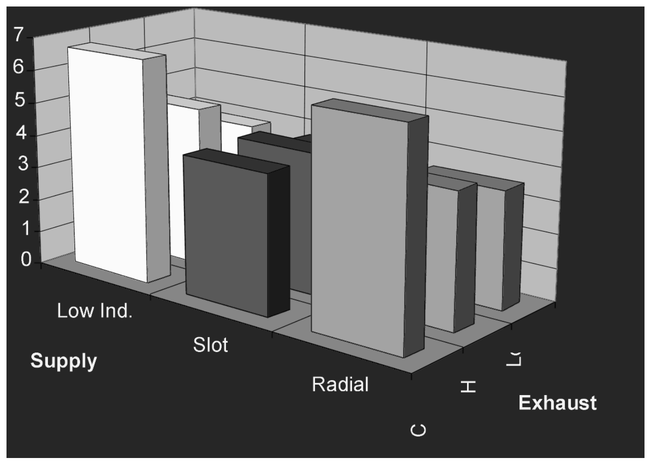

Figure 9 *Comparison of mean cage NH_3 concentration (ppm).*

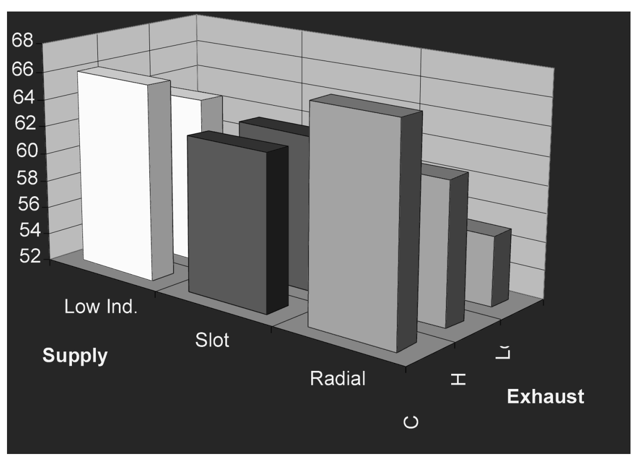

Figure 10 *Comparison of mean cage relative humidity (percent).*

CONCLUSIONS

A series of numerical simulations were considered in which the supply diffuser type and the location of the exhaust grilles were altered. The principal conclusions follow.

- Low-level exhausts produce higher temperatures in the room and cages.
- Low-level exhausts produce the best in-cage ventilation (lowest CO_2 concentrations).
- The slot diffuser seems least sensitive to exhaust position.
- The room concentrations of CO_2 and NH_3 do not show any supply type or exhaust location to be significantly better or worse than any other type.

REFERENCES

Idelchik, I.E. 1989. *Flow resistance: A design guide for engineers*, E. Fried, ed. New York: Hemisphere Publishing Corporation.

Memarzadeh, F. 1998. *Ventilation design handbook on animal research facilities using static microisolators*. Bethesda, Md.: National Institutes of Health, Office of the Director.

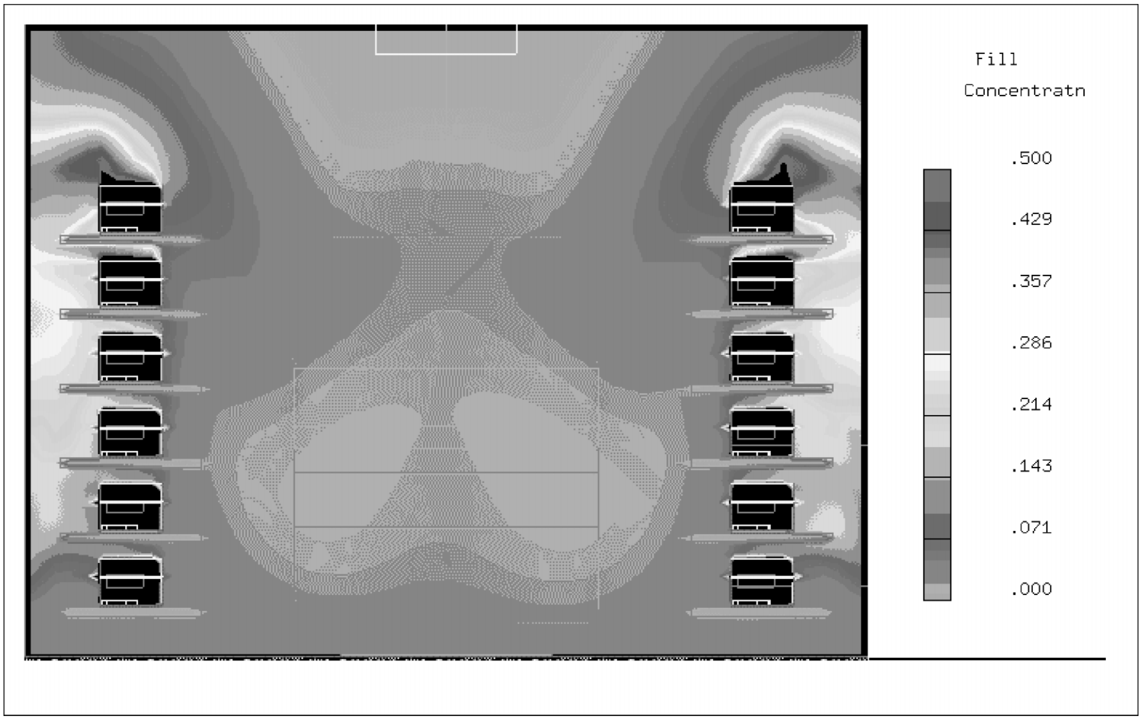

Figure 11 *Room CO_2 distribution (g/kg) with radial diffuser and ceiling exhausts (base case).*

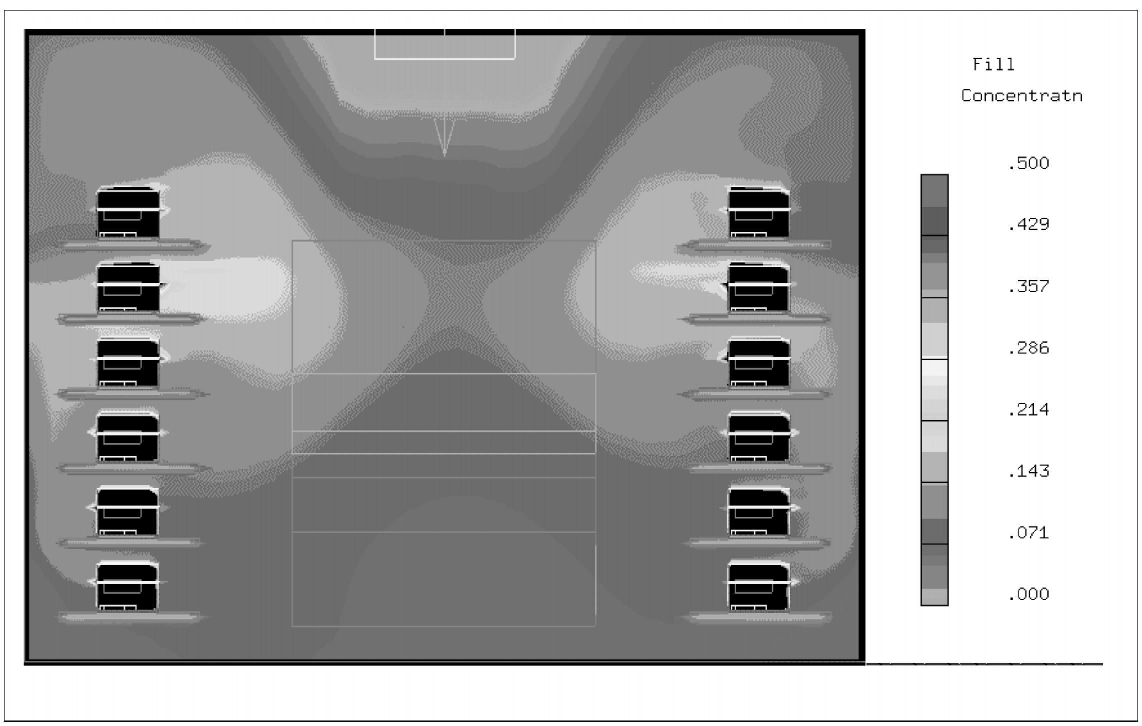

Figure 12 *Room CO_2 distribution (g/kg) with radial diffuser and low-level exhausts (Case3).*