Air mixing in a mechanically ventilated room

J. J. LEONARD and J. B. McQUITTY

Department of Agricultural Engineering, University of Alberta, Edmonton, Alberta T6G 2H1. *Received 3 December 1986, accepted 27 October 1987.*

Leonard, J. J. and McQuitty, J. B. 1988. **Air mixing in a mechanically ventilated room.** Can. Agric. Eng. **30**: 185–189. This paper is concerned with the design of ventilation inlets for animal housing. A relationship is established between the Archimedes number, which has been proposed as a criterion for establishing inlet jet trajectories, and momentum numbers, which have been proposed as criteria for establishing adequate mixing of ventilation and room air. Experimental results are presented in which temperature variations within a room are used as a measure of air mixing. These results show that there is an optimum, rather than a minimum, jet momentum for air mixing. An Archimedes number of approximately five, based on room air temperatures, gave good mixing and satisfactory jet trajectories with all the inlet configurations investigated. More work is required to extend these results to larger rooms.

INTRODUCTION

The design of ventilation systems for animal housing is concerned not only with providing a sufficient volume of air, but also with minimizing the exposure of animals to cold draughts and ensuring adequate mixing of the incoming air with that in the ventilated space. The sizing of fans to provide sufficient air for moisture and temperature control is well established (Huffman and Bird 1986) and criteria for definition of inlet geometries that will provide suitable inlet jet trajectories have been described (Randall and Battams 1979; Leonard and McQuitty 1986a). The relationship between jet trajectory criteria and fan characteristics has also been described (Leonard and McQuitty 1986b).

The problem of establishing criteria to ensure sufficient entrainment of room air by the ventilating air jet and the provision of adequate air mixing has been addressed by several authors. Kaul et al. (1975) proposed criteria based on a jet momentum number and Barber et al. (1982) have suggested that inlets should be capable of providing jets that satisfy trajectory and mixing criteria simultaneously. Barber et al. (1982) proposed that the trajectory criteria be based on an Archimedes number and that the mixing criterion be based on a momentum number.

The initial purpose of this paper is to show that Archimedes and momentum numbers are, in fact, related. Consequently, only one number need be considered in inlet design. Second, measurements of air mixing in a small experimental room are presented and related to momentum numbers. Finally, mixing criteria are suggested on the basis of these measurements with the caveat that they may not be applicable to larger ventilated volumes.

THEORY

The momentum number, as defined by Kaul et al. (1975), was based on an inlet extending the full width of the ventilated room and was obtained by dividing the initial momentum of the jet by the room volume. The initial momentum (M_0) was given by:

$$M_0 = \rho U^2 B h \quad (N) \tag{1}$$

where:
ρ = air density at inlet (kg/m³),
U = inlet air velocity (m/s),
h = vertical width of inlet (m), and
B = room and inlet width (m).
Consequently the momentum number (j) was written:

$$j = \rho U^2 h/XH \ (\mathrm{N/m^3}) \tag{2}$$

where:
X = room length (m), and
H = ceiling height (m).

This momentum number can be generalized to include slots of less than room width by replacing Bh in Eq. 1 with the inlet slot area, A. If this area is expressed in terms of the effective inlet area, A', the following expression for j results:

$$j = \rho Q^2/CBXHA' \ (\mathrm{N/m^3}) \tag{3}$$

where:
Q = volumetric flow rate (m³/s), and
C = inlet discharge coefficient.

Barber (1981) suggested that the momentum number in Eq. 2 could be divided by ρg to give a dimensionless number. This can also be applied to Eq. 3 and the resulting generalized, dimensionless momentum number can be written:

$$J = Q^2/gCBXHA' \tag{4}$$

The momentum number can be related to the Archimedes number that has been proposed as a criterion for determining jet trajectories. This Archimedes number (Ar) may be expressed (Leonard and McQuitty 1986b) in the form:

$$Ar = g(T-T_0)\,(B+H)BHA'/2TQ^2 \tag{5}$$

where:
T = room air temperature (K), and
T_0 = inlet air temperature (K).

Comparison of Eqs. 3 and 5 leads to the relationship:

$$j = \rho g(T-T_0)(B+H)/2TCAr \tag{6}$$

In this equation, B, H, g and C are constant for a given room and, noting that ρ is proportional to $1/T_0$, the expression for momentum number becomes:

$$j = k(T-T_0)/TT_0Ar \tag{7}$$

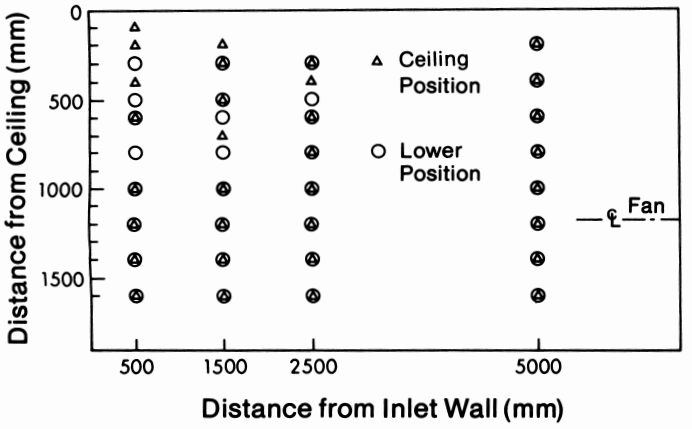


Figure 1. Location of temperature sensors.

where k = a constant.

A similar process may be used to arrive at a relationship between Ar and the dimensionless J:

$$J = k'(T-T_0)/TAr \tag{8}$$

The work of Kaul et al. (1985) indicated that to develop three-dimensional entrainment eddies with the inlet jet, a value of $j>10^{-2}$ N/m^3 was required.

EXPERIMENTAL PROCEDURES

The data on air mixing that are presented and discussed below were obtained during a series of experiments that were designed primarily to investigate inlet air trajectories. The experimental room, the instrumentation used and the procedures adopted have been described previously (Leonard and McQuitty 1984, 1986a) and are presented here in outline only.

Cold air was drawn through various inlet structures into a room 7.2 m long × 5.4 m wide × 1.9 m high. The inlet structures used were a 25-mm, continuous slot extending the full width of the room and a 50-mm slot half as wide as the room. Both inlets were tested in locations at the ceiling and approximately 280 mm below the ceiling. The half-width inlet was centered on the longitudinal centerline of the room.

The presence of animals in the room was simulated using water-filled heating pads which covered approximately 60% of the floor area. The thermostats on the heaters for the pads were set to provide temperatures of approximately 30°C but lack of circulation within the pads caused surface temperatures to vary with the room air temperature. For the tests concerned, T_0 varied from −8°C to −26°C and the difference between T and T_0 varied between about 10°C and 30°C.

Temperatures of heating pad surfaces, inlet air and room air were sensed using matched-curve thermistors. For the room air temperatures, an array of 32 thermistors, arranged as shown in Fig. 1, was interfaced with a microcomputer for data acquisition.

The room was ventilated by an axial-flow fan with variable speed to provide a range of flow rates through the room for each inlet configuration. Each test series began with setting a low flow rate and then consisted of taking temperature readings and photographs of smoke tracers at low and successively increasing flow rates (Leonard 1986).

Although the primary purpose of the temperature data was to delineate inlet jet trajectories, they can be used also to make some inferences about air mixing. The situation, undoubtedly, is complicated by the presence of heating pads but the cold air may be thought of as a thermal tracer. The degree of mixing, therefore, can be related to temperature distributions and uniformity in both horizontal and vertical planes within the ventilated space.

A measure of the variation among these temperatures was required. The measure used was that of a coefficient of variation which may be expressed as:

$$\mathrm{COV} = \sqrt{[\Sigma\delta_i^2/(n-1)]}/\bar{x} \tag{9}$$

where:

COV = coefficient of variation among n points, and

δ_i = deviation from the mean, $\bar{x}$, of the ith point.

For each test, the value of COV was calculated for each vertical group of sensors and also for the lower part of the airspace represented by the bottom four sensors of each vertical group. The location of these lower sensors was constant regardless of inlet height, thus providing a good basis for comparison of the mixing characteristics of the various inlets.

To maintain consistency between experimental runs, data for lower airspace temperatures were normalized by expressing them in terms of dimensionless temperature differences according to the following formula:

$$\Delta T_n = (T_n - T_0)/(T_d - T_0) \tag{10}$$

where:

ΔT_n = dimensionless temperature difference at location n,

T_n = temperature at location n,

T_d = temperature downstream of exhaust fan, and

T_0 = temperature at inlet.

The coefficient of variation of these lower sensors was denoted by $\mathrm{COV_L}$.

Another measure of air mixing and entrainment is the variation of temperature across the jet at some distance from the orifice. As the jet entrains air from the surroundings, the temperature profile flattens out until, finally, the jet is indistinguishable from the room air. In this case, the evaluation of temperatures at right angles to the jet centerline was not possible, but the vertical variation of temperature at the last group of sensors (5 m from the inlet) could give an indication of entrainment, especially for higher velocity jets (i.e., jets with low Archimedes numbers). This variation was represented by the coefficient of variation of temperatures indicated by these sensors, $\mathrm{COV_5}$.

Because temperatures 5 m from the inlet tended to be close to the outlet duct temperature, absolute temperatures rather than temperature differences were used in the calculation of $\mathrm{COV_5}$. Those cases where the inlet jet had dispersed within 5 m of the inlet wall were ignored in the analysis of $\mathrm{COV_5}$.

As well as an evaluation of the mixing and entrainment performance of the jets, an index of this performance was required for possible use as a design criterion. Both Archimedes and momentum numbers were considered for this purpose. The equivalence of these two numbers has been explored above and the plotting of the mixing indicators $\mathrm{COV_L}$ and $\mathrm{COV_5}$ against both Ar and J was considered to be unneccessary. Primarily for convenience of scaling, both indicators were plotted only against the dimensionless momentum number, J.

RESULTS

Horizontal Temperature Variations

The most comprehensive of the two indicators was the coefficient of variation of all the temperatures observed in the lower part of the airspace, $\mathrm{COV_L}$. This is plotted against J, along with

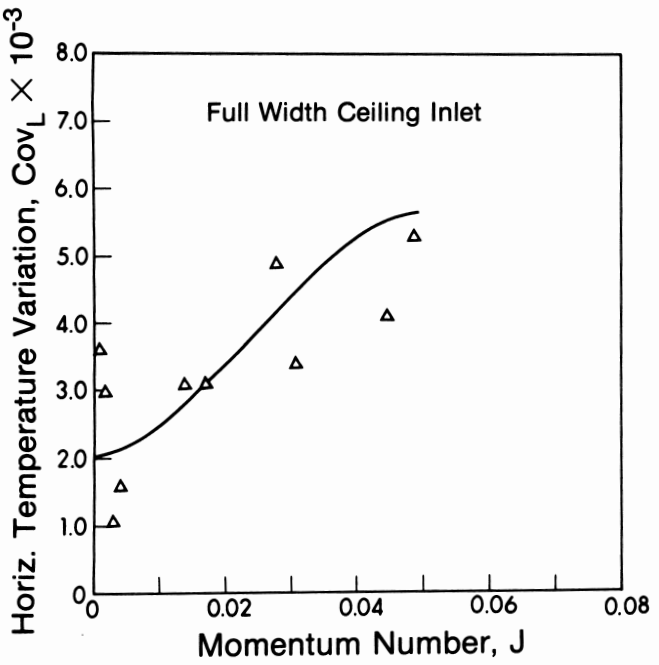


Figure 2. Plot of COV_L versus J (ceiling full-width inlet).

the best-fit cubic functions obtained by least-squares regression; for each inlet configuration, in Figs. 2–5.

The equations to these curves, given in Table I, are not necessarily the best fit equations. Rather, they were used to provide a consistent method of quantifying the minima that are exhibited by the data. Values of J coincident with these minima were determined by setting the derivatives of the cubic functions equal to zero and solving the resulting quadratic equations. They are as follows:

Ceiling full-width inlet (FC), $J = .002$
Lower full-width inlet (FL), $J = .030$
Ceiling half-width inlet (HC), $J = .013$
Lower half-width inlet (HL), $J = .019$

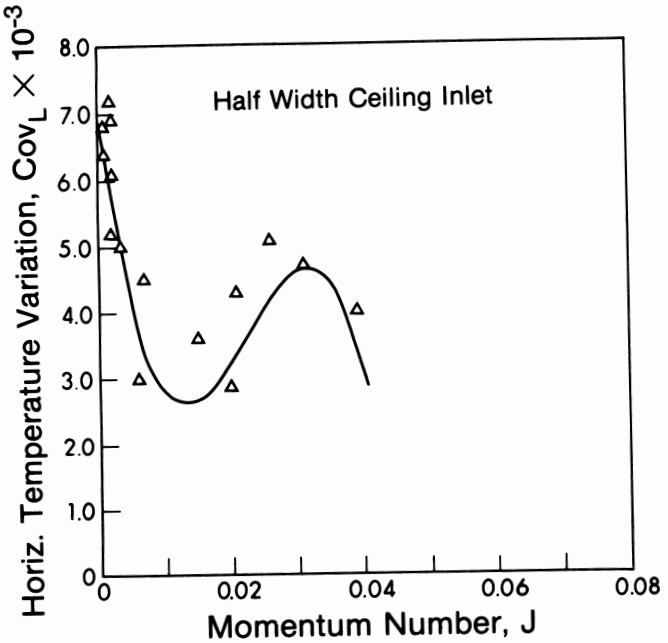


Figure 3. Plot of COV_L versus J (lower full-width inlet).

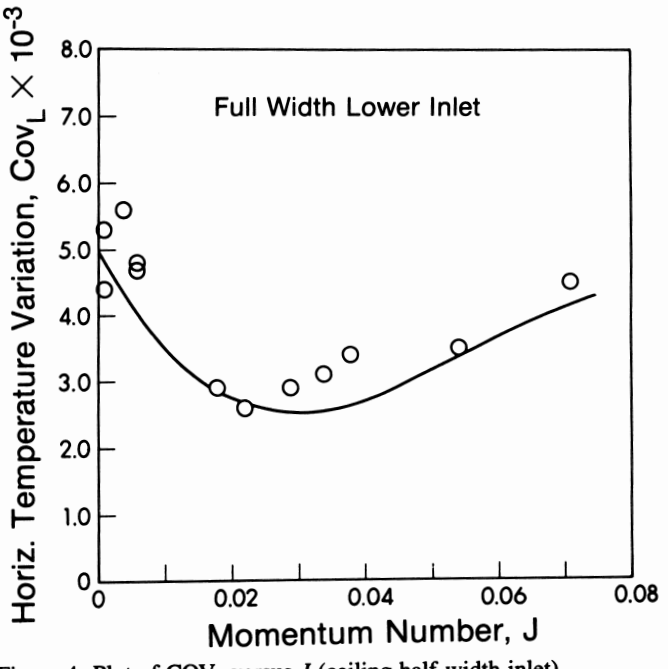


Figure 4. Plot of COV_L versus J (ceiling half-width inlet).

The fact that in each case there appears to be a value of J for which the variation in temperature is minimized is, in itself, significant. The implication of this result is that for mixing and uniform supply of fresh air there is an optimum ventilation rate rather than a minimum rate as proposed by Kaul et al. (1975) and Barber et al. (1982).

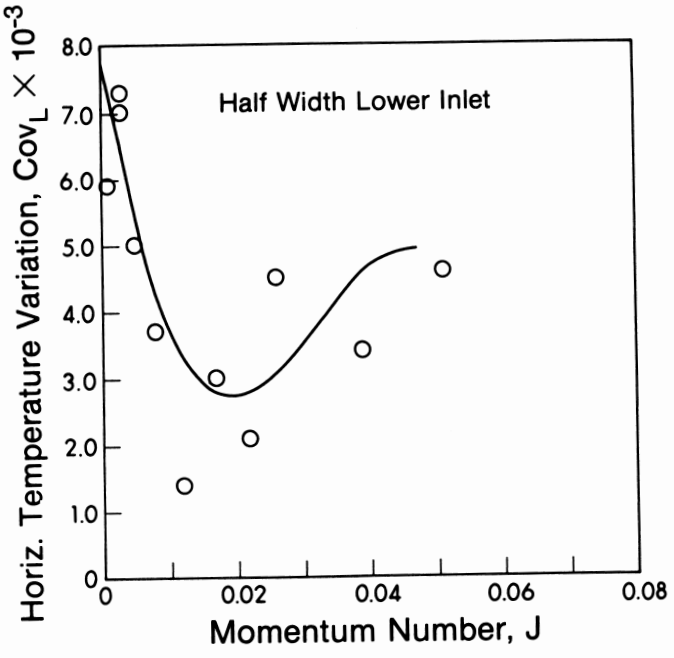


Figure 5. Plot of COV_L versus J (lower half-width inlet).

Table I. Cubic equations relating COV_L and J

Inlet	Equation
FC	$COV_L = 0.002 + 0.013J + 3.76J^2 - 51.2J^3$
FL	$COV_L = 0.005 - 0.19J + 4.33J^2 - 25.6J^3$
HC	$COV_L = 0.007 - 0.79J + 42.85J^2 - 639.8J^3$
HL	$COV_L = 0.008 - 0.64J + 23.68J^2 - 244.2J^3$

In fact, even the lowest momentum numbers measured were greater than the minimum values proposed by the above authors. This is noteworthy since observations and photographs of the jets indicated that the mixing effect of these jets was minimal, and primary eddies were not set up as predicted by the momentum number criteria that have been proposed. These criteria were developed for isothermal jets, and the results reported here seem to indicate that different criteria are required for nonisothermal conditions.

The minima identified with the cubic regression functions may be taken as indicators of such criteria. For comparison, the minimum value of j recommended by Kaul et al. (1975) was 10^{-2} N/m^3 which, when made nondimensional, transforms into a value of $J \simeq 7.4 \times 10^{-4}$ for the air densities used in these experiments. This value is less than half of that required to give the minimum temperature variation for the full-width ceiling inlet which, itself, was an order of magnitude smaller than that for the other inlets.

The results from the full-width, ceiling inlet differ from those of the other inlets, not only in the much lower value of J required for minimum temperature variation, but also in the generally lower level of variation over the range of J. These differences may be explained by the greater tendency of jets from the full-width ceiling inlet to adhere to the ceiling due to the Coanda effect (Leonard and McQuitty 1986a).

Low-velocity jets from the other inlet configurations tended to drop within the first 0.5 m of entry. At very low flow rates these jets would dissipate rapidly and have little effect on temperatures at lower levels in the airspace. With a slight increase in flow rate, the jets would have sufficient energy to affect the lower level temperatures, thereby giving the peak coefficients of variation at low values of J. As the flow rate increased, the jets tended increasingly to remain elevated and to dissipate in the upper part of the airspace, thereby giving a decrease in the coefficients of variation. Beyond the COV_L minimum, primary circulation patterns and the spreading of the temperature profile combined to bring colder air into the lower airspace further from the inlet. This resulted in an increasing coefficient of variation.

Of the observed ceiling jets from the full-width inlet, only one had sufficiently low momentum to drop to the floor within 0.5 m of entry. The coefficient of variation decreased over a much narrower range of J (Fig. 2) since the Coanda effect became significant at lower flow rates than for other inlets and had the effect of shifting the coefficient of variation minimum to the left. Because the jets from this inlet were held in the upper airspace, especially at low velocities, the temperature variations were lower than with the other inlet configurations.

Vertical temperature distribution

The vertical temperature distribution was assessed using the group of sensors located 5 m from the inlet wall. Again, coefficients of variation were calculated and plotted against J, but, unlike those of the horizontal temperature variation data, these plots showed no coherent pattern.

The data were distorted by the fact that of the jets with sufficient energy to penetrate to the line of sensors some would have been adhering to the ceiling while some would have separated. The temperature profiles of separated and adhering jets would be of different shapes and, therefore, not comparable in this manner.

The jets least affected by attachment to the ceiling were those from the half-width inlet at the lower position. The data from these jets did suggest a minimum variation in the vertical temperature distribution at values of J similar to those that gave minimum horizontal temperature variations. This suggestion also was apparent in the data for the half-width inlet in the top position, but not for the two full-width inlets.

DESIGN RELEVANCE

Analysis of horizontal temperature distributions in the ventilated room indicates that even if jet trajectory criteria (Leonard and McQuitty 1986a) are satisfied, mixing and uniformity of air distribution in the lower airspace may be impaired if Ar is too small. Optimum mixing occurred at different values of J (or Ar), depending on inlet type, while the variation of temperature associated with these flow rates depended also on the inlet type.

Although optimum values of Ar could be postulated for each type of inlet, it would be desirable for design purposes to have a general rule or single value of Ar that could be applied universally, regardless of inlet type. Examination of Figs. 2–5 and the equations of Table I leads to the conclusion that a value of $Ar = 5$ would give good mixing performance in all cases. This corresponds to a value of $J = 0.013$ which, when substituted in the equations of Table I, would give a coefficient of variation of temperature of approximately 0.003.

The above discussion is based on observed, albeit limited, experimental evidence. However, the experimental observations were carried out under idealized conditions in a small room and may not translate easily into practical designs in large, animal housing volumes. Further work is required in this area. An analysis of what these criteria mean in terms of actual inlet design and operation may be found elsewhere (Leonard and McQuitty 1986b).

CONCLUSIONS

The use of both momentum and Archimedes numbers as mixing and trajectory criteria (Barber et al. 1982) has been shown to be superfluous by virtue of a clear relationship between Ar and J.

The degree of air mixing in a small room was evaluated by analyzing the variation in temperature in the lower part of the ventilated space. With each inlet configuration tested, an optimum ventilation rate for air mixing was apparent. These rates corresponded to values of J that were much larger than the criteria proposed by previous researchers (Kaul et al. 1975; Barber et al. 1982) using isothermal jets. Different criteria are required for nonisothermal jets.

For all inlet types, jets with Ar values of less than 5 would give good trajectories and mixing performance in the room studied. Work is needed to confirm these findings in larger air volumes.

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