Effect of air recirculation on airspeeds at animal level

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Deurloo, J. A., Feddes, J. J. R., Leonard, J. J. and Darby, D. E. 1990. Effect of air recirculation on airspeed at animal level. Can. Agric. Eng. 32: 129-134. The effects of recirculated air on the air speed within the lower 0.5 m of a room simulating a small pig weanling room were studied. Recirculation rates for the chamber were 4.8, 6.9, and 8.8 L/s per m² of floor area and the jet velocities were 3.2, 4.5, and 5.4 m/s. A split-plot experimental design consisted of three recirculation rates, three jet velocities and three replicates. Only the rate of 4.8 L/s per m² of floor area was significantly different from the other recirculation rates in terms of affecting the air speed within the animal zone. The jet velocities had no significant effect on the air speeds. The mean air speed at animal level for all jet velocities was 0.39 m/s while that for the recirculation rates of 6.9 and 8.8 L/s per m² was 0.46 m/s and that for 4.8 L/s per m² was 0.26 m/s. A mean Jet Momentum value of 0.02 N/m³ yielded a mean air speed at animal level of 0.30 m/s. The coefficient of discharge for a plywood duct ranged from 0.61 to 0.80 (mean 0.74) for the recirculation rates and jet velocities considered.

INTRODUCTION

Many modern livestock confinement barns in Canada use a ventilation system consisting of exhaust fans and continuous slot fresh air inlets. The exhaust fans create a negative static pressure in the barn (relative to atmospheric pressure) which causes air to be drawn in through the air inlets. The air inlets are designed to direct the incoming air along the ceiling at a high speed so the colder fresh air mixes with warm room air before it enters the animal zone. In hot weather, a high ventilation rate must be employed; the typical summer maximum ventilation rate may be 10-15 times as great as the typical winter minimum ventilation rate.

At winter minimum ventilation rates, it is difficult to adjust a continuous slot inlet to maintain a high inlet air velocity uniformly along the slot length. The inlet has to be straight and true and the building otherwise nearly airtight, which is seldom achieved. Also, the incoming fresh air is usually much colder and more dense than the inside air, causing the cold air to sink to the floor as its momentum is dissipated.

Canadian livestock producers have generally been dissatisfied with the performance of continuous slot air inlet systems in cold weather (Hodgkinson and Barber 1986). Recirculation ducts are being promoted for livestock buildings by Canadian engineers because recirculation maintains stable air circulation patterns, even at low winter ventilation rates, and results in good mixing of inlet air and room air in the space above the animal zone.

The design parameters of recirculation ducts have been the subject of a number of studies (Carpenter 1972; Perry 1973; Saunders and Albright 1984; Brundrett and Vermes 1987) but these studies were concerned mainly with the air distribution along the length of the duct, or the characteristics of the air jets leaving the ducts. To date, very little research has investigated the effects of recirculation on the ambient conditions in the animal zone. Ogilvie et al. (1988) studied recirculation flows and their effects on air speeds in the animal zone.

Early recirculation systems used round polyethylene ducts, which were simple to install and low in cost. Rectangular plywood ducts with removable bottoms are becoming more common because they are more attractive, easier to clean, and take up less headroom. Most previous research involved polyethylene ducts, which have much thinner walls, and a round, rather than rectangular, cross-section. The thicker walls of a plywood duct may have an effect on the path of the air jets leaving the outlets, which may affect the uniformity of air distribution along the duct.

The objective of this project was to investigate the influence of plywood recirculation duct design parameters on the mean air speed in the animal zone. For this study, the parameters investigated were:

(1) recirculation rate; and
(2) outlet air jet velocity.

The animal zone was defined as the airspace within 0.5 m of the floor, since this would be the zone of occupation for young pigs and poultry, the animals most sensitive to drafty conditions.

EXPERIMENTAL FACILITIES

Experimental data were collected in the ventilation research chamber at the University of Alberta farm at Ellerslie. A plywood recirculation duct was installed along the top of one wall of the chamber. The chamber was divided by a polyethylene curtain so that the room under study was 5.4 m long x 4.0 m wide x 1.83 m high, to represent one-half of a 5.4 m x 8.0 m wide pig weanling room with a recirculation duct in the center (Fig. 1). The room was empty, except for the recirculation duct, video camera, light source, and four measuring stations on the floor. The ceiling was approximately 0.6 m lower than conventional ceilings.

The recirculation duct was 200 mm x 250 mm in cross-section and 4.6 m long, constructed from 12-mm fir plywood and 38-mm x 38-mm framing (Fig. 1). A 250-mm-diameter variable-speed axial flow fan (Canarm Model S10-B2) was installed at one end of the duct. The output of the fan was controlled by a variable speed controller, and the speed of the fan was monitored by measuring the output voltage of the variable speed controller. Static pressure at the fan was measured from a pressure tap located immediately downstream from the fan with a micromanometer (accurate to 0.1 Pa). A relationship between static pressure at the fan, fan supply voltage, and fan output was determined at the beginning of this project (Deurloo et al. 1988). Only room air was recirculated with no outside air being introduced, therefore the air from the duct was at same temperature as room air.
EXPERIMENTAL PROCEDURE

The main body of the project was set up as a 3 × 3 split-plot experimental design, replicated three times. Three recirculation rates (5, 7 and 9 L/[s.m² of floor area]) and three jet exit velocities (3, 4 and 5 m/s) were selected. The jet velocity is a calculated value equal to the output of the recirculation fan divided by the total outlet area, i.e., before correction for vena contracta (Table I). The outlet holes on the side of the duct were 50 mm in diameter and number and spacing of the holes were altered as required to obtain the desired jet exit velocity at each recirculation rate.

The output of the fan was estimated by measuring the static pressure at the fan and the output voltage of the variable speed controller. The direction of the airflow at animal level was determined visually. The airspeed at animal level was measured by filming smoke puffs with a video camera directed perpendicular to direction of air (Fig. 3). The smoke puffs were released with a vertical direction at a point 10 cm above the floor, so that the smoke was between 15 and 50 cm from the floor as it passed in front of the camera. The airspeed was determined by counting the number of frames as the smoke puff travelled a distance of 20 cm, knowing that the speed of the camera was 30 frames per second. Ten smoke puffs were filmed at each test station and the mean airspeed was calculated. The mean airspeeds at the 4 stations were averaged to obtain the mean airspeed in the room.

Jet momentum

Barber et al. (1982) suggested that the Jet Momentum Function ($J_i$) could provide a good indicator of air mixing. This function was defined previously by Kaul et al. (1975) and may be expressed as follows:

$$ J_i = \frac{\rho \cdot m \cdot v}{V} \quad \text{N/m}^3 \quad (1) $$

where:

- $v$ = jet exit velocity (m/s),
- $m$ = recirculation rate (m³/s),
- $V$ = room volume (m³) and
- $\rho$ = density of jet air (1.1 kg/m³ @ 687-m altitude and 20°C).

The jet velocity is the actual air velocity at the vena contracta. To calculate this velocity, the discharge coefficient must be calculated. To estimate the discharge coefficient, the outlet area, the fan output and the static pressure at the fan and end of the duct must be measured. The fan output can be described as follows:

$$ Q_f = \frac{\sum Q_i}{n} \quad \text{L/s} $$

where:

Table I. Parameters used in project

<table>
<thead>
<tr>
<th>Trial</th>
<th>Number of 50-mm holes</th>
<th>Total outlet area (cm²)</th>
<th>Recirculation fan output (L/s)</th>
<th>Recirculation rate (L/(s.m²))</th>
<th>Jet exit velocity†</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>600</td>
<td>190</td>
<td>8.8</td>
<td>3.2</td>
</tr>
<tr>
<td>B</td>
<td>22</td>
<td>440</td>
<td>140</td>
<td>6.5</td>
<td>3.2</td>
</tr>
<tr>
<td>C</td>
<td>15</td>
<td>300</td>
<td>100</td>
<td>4.6</td>
<td>3.3</td>
</tr>
<tr>
<td>D</td>
<td>22</td>
<td>440</td>
<td>190</td>
<td>8.8</td>
<td>4.3</td>
</tr>
<tr>
<td>E</td>
<td>17</td>
<td>340</td>
<td>160</td>
<td>7.4</td>
<td>4.7</td>
</tr>
<tr>
<td>F</td>
<td>12</td>
<td>240</td>
<td>110</td>
<td>5.1</td>
<td>4.6</td>
</tr>
<tr>
<td>G</td>
<td>18</td>
<td>360</td>
<td>190</td>
<td>8.8</td>
<td>5.3</td>
</tr>
<tr>
<td>H</td>
<td>14</td>
<td>280</td>
<td>150</td>
<td>6.9</td>
<td>5.4</td>
</tr>
<tr>
<td>I</td>
<td>9</td>
<td>180</td>
<td>100</td>
<td>4.6</td>
<td>5.6</td>
</tr>
</tbody>
</table>

† Average jet velocity across opening.
The airflow through each opening can be described in terms of the discharge coefficient $(C_d)$, area of opening $(A_0)$, and static pressure in the duct adjacent to opening $(P_i)$. The relationships are as follows:

$$Q_i = C_d A_0 (2P_i/\rho)^{0.5}$$  \( (3) \)

where:

$$P_i = \text{static pressure at hole } i.$$  

When assuming that friction losses are negligible, the static pressure at each hole becomes:

$$P_{i+1} = P_i + (\rho/2)(V_i^2 - V_{i+1}^2)$$  \( (4) \)

where:

$$V_i = \text{air velocity in the duct at hole } i.$$  

At the closed end of the duct, the airflow rate is zero and the static pressure is known. The airflow out of the last hole can be estimated from the static pressure using Eq. 3 if a value of $C_d$ is assumed. The airflow out of the hole is added to the airflow in the duct downstream from the hole to obtain the airflow rate in the duct upstream from the hole. From this, the velocity change in the duct can be calculated, and then the static pressure at the previous hole can be estimated, using Eq. 4. This process is repeated for each hole, back to the fan. Then the total airflow rate out of the holes is compared to the airflow in the duct upstream from the hole. If the airflow rates do not match, then $C_d$ is adjusted and the calculations are repeated. This trial-and-error approach is easily handled by a computer (Saunders and Albright 1984).

**RESULTS AND DISCUSSION**

**Recirculation rate**

Air patterns created by the recirculated air were considered to be stable. In all cases, air jets travelled along the ceiling to the opposite wall, then down the side wall and along the floor back to the recirculation duct.

As the air moved along the floor some air also moved upward to be entrained by the air jets near the ceiling. Air usually was not entrained by the same jet each time but travelled in a large spiral towards the recirculation fan.

Figure 4 shows typical air speeds (m/s) and directions of air movement at points in the animal zone, 1 m apart. Note the influence that the recirculation fan has on the direction of the air movement in one end of the room, even at distances over 4 m away from the fan. Also note that the air speeds tend to be less at points nearer to the duct and nearer to the center of the room.

Air speeds in the animal zone showed a wide range of fluctuation in values at each of the four test points. Nevertheless, means were taken for each test and these were tested statistically using the Duncan test (Steele and Torrie 1980). Table II indicates that the airspeeds in the animal zone for a recirculation rate of 4.8 L/(s.m² of floor area) were significantly different (at the 5% level) from those for recirculation rates of 6.9 and 8.8 L/(s.m² of floor area) (Fig. 5). This implies a nonlinear relationship between the recirculation rate and the airspeed in the animal zone.

Piglets less than 8 wk old have faster growth and better feed conversion at air speeds of less than 0.3 m/s, even at optimal room temperatures (Yao et al. 1986). Room temperatures less than optimal increase the effect of drafts on the piglets (Riskowski and Bundy 1986). Currently recommended recirculation rates of 6–7 L/(s.m² of floor area) (Darby and Dill 1988) appear to be too high, based on the results shown in Table II. On the basis of these tests, a better guideline for recirculation rates seems to be 4 to 5 L/(s.m² of floor area). This may in part be due to a low ceiling, short jet path and no floor obstructions. However, Ogilvie et al. (1988) suggested the same values.

**Jet velocities**

Table III indicates, at a given recirculation rate, that the average exit velocity of the air leaving the recirculation duct had little or no statistically significant effect on the airspeed in the animal zone over a range of exit velocities from 3.2 m/s to 5.4 m/s, a range commonly regarded as desirable duct design criteria. This is illustrated in Fig. 5.

**Jet momentum ($J_j$)**

A $J_j$ value was calculated for each recirculation rate and jet exit velocity giving a total of nine values. The average jet velocities were divided by their respective $C_d$ values to obtain vena contracta velocities (Table IV). These values were correlated
Table II. Effect of recirculation rate on airspeed in the animal zone

<table>
<thead>
<tr>
<th>Recirculation rate (L/s.m² of floor area)</th>
<th>Mean airspeed in animal zone† (m/s)</th>
<th>Station (see Fig. 3):</th>
<th>Mean of stations 1–4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4.8</td>
<td>0.21a</td>
<td>0.23a</td>
<td>0.28a</td>
</tr>
<tr>
<td>6.9</td>
<td>0.37b</td>
<td>0.46b</td>
<td>0.37ab</td>
</tr>
<tr>
<td>8.8</td>
<td>0.36b</td>
<td>0.50b</td>
<td>0.45b</td>
</tr>
</tbody>
</table>

† Air speeds are pooled averages at three levels of jet exit velocity.

a,b Values in a column followed by the same letter are not significantly different at the 5% level using Duncan’s test.

![Diagram](image)

Fig. 5. Mean air speed in the animal zone for three recirculation rates and three jet exit velocities.

Table III. Effect of exit air velocity on airspeed in the animal zone

<table>
<thead>
<tr>
<th>Exit air velocity (m/s, based on fan output and total outlet area)</th>
<th>Mean airspeed in animal zone† (m/s)</th>
<th>Station (see Fig. 3):</th>
<th>Mean of stations 1–4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3.2</td>
<td>0.31a</td>
<td>0.39ab</td>
<td>0.36a</td>
</tr>
<tr>
<td>4.5</td>
<td>0.29b</td>
<td>0.35a</td>
<td>0.36a</td>
</tr>
<tr>
<td>5.4</td>
<td>0.34a</td>
<td>0.46b</td>
<td>0.37a</td>
</tr>
</tbody>
</table>

† Air speeds are pooled averages at three levels of recirculation rate.

a,b Values in a column followed by the same letter are not significantly different at the 5% level using Duncan’s test.

Table IV. Discharge coefficients

<table>
<thead>
<tr>
<th>Trial</th>
<th>Recirculation rate (L/s)</th>
<th>Jet exit velocity†</th>
<th>Air speed at animal level (m/s)</th>
<th>C_d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>190</td>
<td>5.2</td>
<td>0.53</td>
<td>0.61</td>
</tr>
<tr>
<td>B</td>
<td>140</td>
<td>4.2</td>
<td>0.49</td>
<td>0.77</td>
</tr>
<tr>
<td>C</td>
<td>100</td>
<td>4.1</td>
<td>0.23</td>
<td>0.80</td>
</tr>
<tr>
<td>D</td>
<td>190</td>
<td>6.2</td>
<td>0.48</td>
<td>0.69</td>
</tr>
<tr>
<td>E</td>
<td>160</td>
<td>6.0</td>
<td>0.39</td>
<td>0.78</td>
</tr>
<tr>
<td>F</td>
<td>110</td>
<td>6.6</td>
<td>0.21</td>
<td>0.70</td>
</tr>
<tr>
<td>G</td>
<td>190</td>
<td>6.6</td>
<td>0.42</td>
<td>0.80</td>
</tr>
<tr>
<td>H</td>
<td>150</td>
<td>6.9</td>
<td>0.41</td>
<td>0.78</td>
</tr>
<tr>
<td>I</td>
<td>100</td>
<td>7.4</td>
<td>0.33</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Avg. 0.74

† Vena contracta.
with the mean floor air speeds as shown in Fig. 6. Two points, labelled A and B in Fig. 6 appeared to be outliers for unknown reasons. When the points were included in the regression equation, the $R^2$ value was 0.30. When the points were removed, the relationship between $J_J$ and air speed was as follows:

$$AS = 0.081 + 10.8 J_J \quad R^2 = 0.78$$

where:

$AS$ = air speed (m/s).

This relationship may not be applicable to rooms in which the duct-wall distance is greater than three ceiling heights. Nevertheless, it provides a good basis for an order-of-magnitude approach to determining a recommended value of $J_J$. If the upper limit of mean air speed at animal level is set at 0.30 m/s (Yao et al. 1986), the upper limit of $J_J$, calculated from the above relationship, is 0.02 N/m$^3$. This is close to the equivalent minimum value recommended by Kaul et al. (1975) to achieve satisfactory air mixing with an isothermal jet ($J_J$ approximate $10^{-2}$ N/m$^3$) and also agrees very well with the Jet Momentum Number ($J$) presented by Ogilvie et al. (1988).

Because of this good agreement with previous work, the exclusion of the two points mentioned above appears to be justified and a maximum design value for $J_J$ of about 0.02 seems appropriate for most isothermal applications.

The work of Leonard and McQuitty (1988) suggests that, for non-isothermal conditions, a $J_J$ value of an order of magnitude higher could be required to achieve optimum mixing. These authors, however, did not monitor air velocities at animal level but, instead, relied on temperature differences to provide an indication of mixing.

CONCLUSIONS

(1) Currently recommended winter recirculation rates of 6 to 7 L/(s.m$^2$ of floor area) may be higher than necessary for weanling pigs. A rate of 4 to 5 L/(s.m$^2$ of floor area) provides air speeds of 0.3 m/s at animal level in an empty room.

(2) No statistically significant relationship exists between the jet exit velocity (3–5 m/s) and the speed in the animal zone.

(3) The mean discharge coefficient for a plywood duct for the conditions in this experiment was 0.74.

(4) Air velocity at animal level can be estimated from Jet Momentum values for air speeds less than 0.5 m/s. For isothermal applications, a maximum value of $J_J = 0.02$ N/m$^3$ is appropriate for design purposes.

REFERENCES


