Discharge coefficients for openings in metal or plywood walls of recirculation ducts

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Patsula, R., Feddes, J.J.R. and Leonard, J.J. 1992. Discharge coefficients for openings in metal or plywood walls of recirculation ducts. Can. Agric. Eng. 34:359-363. The effect of recirculation duct air outlet materials on the coefficient of discharge values (C_d) were studied. Opening diameters investigated were 50-mm sheet metal, 50-mm, and 55-mm plywood. Static pressures, duct velocities, and opening exit velocities were measured along a length of 5-m rectangular plywood duct. Values of C_d were calculated directly from the measured static pressure and duct velocity values. The mean C_d values for 50-mm metal, 50-mm plywood, and 25-mm plywood openings were 0.70, 0.72, and 0.71, respectively for exit velocities of 5 m/s. For each type of opening, C_d values decreased by 0.0133 per metre of duct length. The mean static pressure and duct airspeed was 27 Pa and 2 m/s, respectively. Aperture ratio was 0.785. Opening exit velocities were approximately 5 m/s. The increase in static pressure and decrease in the C_d value along the length of the rectangular duct resulted in a very uniform distribution of airflow along the duct.

The effect of the materials of the sorts d’air sur le coefficient de décharge (C_d) a été étudié. La section des orifices à l’étude était faite de tôle de 50 mm et de contreplaqué de 50 mm et 25 mm. La pression statique et la vitesse de déplacement de l’air dans le conduit et à la sortie ont été mesurées dans un conduit de contreplaqué rectangulaire de 5 mètres de long. Les valeurs de C_d ont été calculées directement à partir de la pression statique mesurée et de la vitesse de déplacement de l’air dans le conduit. Les valeurs moyennes de C_d pour les orifices de tôle de 50 mm et de contreplaqué de 50 mm et de 25 mm étaient de 0.70, 0.72 et 0.71 respectivement pour une vitesse de sortie de 5 m/s. Pour chaque type d’orifice, la réduction des valeurs du C_d était de 0.0133 par mètre de longueur de conduit. La pression statique et la vitesse moyenne de déplacement de l’air dans le conduit étaient de 27 Pa et de 2 m/s respectivement. La relation d’ouverture était de 0.785. La vitesse de sortie atteignait environ 5 m/s. L’augmentation de la pression statique et la diminution du C_d sur toute la longueur du conduit rectangulaire ont produit une distribution très uniforme du débit d’air dans le conduit.

INTRODUCTION

All modern livestock barns require ventilation to remove aerial contaminants. During warm months, air enters the airspace at sufficient velocities to promote suitable mixing. However, during cold weather, air velocities through adjustable, continuous-slot inlets can be low and non-uniform causing cold drafts, poor mixing of the airspace and varying temperatures in the animal zone.

By integrating a recirculation duct with an existing conventional inlet, uneven air distributions can be avoided (Hodgkinson and Barber 1986, Duerloo et al. 1990). A recirculation duct is typically located below a conventional slot inlet with openings spaced regularly along its length, and directed parallel to the incoming air. A fan at one end of the duct draws air from the room and discharges it through the duct openings. Air entering the room through the slot inlet is entrained with the recirculated air resulting in a composite flow of higher velocity and, thus better mixing of the incoming and resident air (Fig. 1).

Little research has been carried out on the operational characteristics of recirculation ducts used in livestock housing that are made of plywood and operate at static pressures of less than 35 Pa. One parameter affecting duct operation is the coefficient of discharge (C_d) of outlets along the length of the duct. The coefficient of discharge relates theoretical air velocity through an opening to the actual velocity. The discrepancies in velocities are related to energy losses through the orifice. Therefore, by examining factors which affect the C_d value, operation of the recirculation duct can be defined more accurately. For example, if the mean C_d value for each duct opening is known, together with the desired flow rate, then the necessary static pressure in the duct can be determined. With that data and fan performance curves, a proper fan can be selected for the duct. The objective of this project was to determine if C_d values are influenced by outlet wall materials such as plywood and sheet metal.

DESIGN PARAMETERS

Saunders and Albright (1984) and Brundrett and Vermes (1987) suggest that C_d is dependent on outlet size, duct static pressure, airflow rate and opening material. The airflow through an opening can be related to the coefficient of discharge, area of opening, and static pressure in the duct adjacent to the opening as:

\[ Q_d = C_d \times A_o \times (2P_d \times \rho)^{0.5} \]  \hspace{1cm} (1)

where:

- \( Q_d \) = airflow rate through opening (m\(^3\)/s).
- \( A_o \) = cross-sectional area of opening (m\(^2\)),
- \( P_d \) = duct static pressure at opening (Pa), and
- \( \rho \) = density of air (kg/m\(^3\)).

Air flow through an opening can also be described in terms of the difference between the airflow in the duct upstream from the opening and that downstream from the opening. The relationship is:

\[ Q_o = (V_{di} - V_{do}) \times A_d \times n^{-1} \]  \hspace{1cm} (2)
where:
\[ V_{d1}, V_{d2} = \text{mean velocity upstream and downstream from the opening, respectively (m/s)}, \]
\[ A_d = \text{cross-sectional area of duct (m}^2\text{)}, \]
\[ n = \text{number of openings between} \ V_{d1} \ \text{and} \ V_{d2}. \]

Equations 1 and 2 can be combined into Eq.3 such that the measured \( P_o \) and \( V_d \) values can be used to predict \( C_d \) values along the length of the duct.

\[ C_d = \left( V_{d1} - V_{d2} \right) A_d n^{-1} A_o^{-1} \left( 2 \ P_o/\rho \right)^{0.5} \tag{3} \]

The airflow introduced into the duct by the fan should equal the sum of the measured airflows from each opening. If the airflow from any given opening is measured by placing a tube with a similar opening diameter downstream from the opening, the fan output can be expressed as:

\[ Q_f = \sum_{i=1}^{n} \left( V_{ci} A_i / K \right) \tag{4} \]

where:
\[ Q_f = \text{fan flow rate (m}^3/\text{s)}, \]
\[ V_{ci} = \text{measured centre line velocity in tube at width opening (m/s)}, \]
\[ K = \text{ratio of centre line to mean velocity, and} \]
\[ A_i = \text{cross-sectional area of measuring tube (m}^2\text{)}. \]

The value of \( K \) varies with Reynolds Number (Ower and Parkhurst 1977) and is, therefore, dependent on the air velocity and the tube diameter. For the velocities and tubes used in this investigation, \( K \) has an approximate value of 1.25.

**EXPERIMENTAL FACILITIES AND PROCEDURES**

A 5-m long, plywood, rectangular duct with a 250-mm by 400-mm cross-section was constructed (Fig.2). The duct walls consisted of 12-mm sanded spruce plywood. A 400-mm diameter, variable-speed propeller fan provided airflow to the recirculation duct. A flow straightener was installed 1-m downstream from the fan to reduce swirl. The plywood and the sheet steel outlet sidewalls were 12 mm and 1.5 mm in thickness, respectively. Forty, 50-mm diameter outlet holes were spaced 150-mm o.c., starting at a distance of 4.3-m from the fan. For the 25-mm diameter openings in a plywood sidewall, pairs of openings, located one above the other, were spaced 75-mm o.c. horizontally along the duct. In all cases the aperture ratio (i.e., the ratio of total hole area to duct cross sectional area) was 0.785.

Fan output was adjusted to provide a flow rate of approximately 0.4 m\(^3\)/s. At this flowrate, the static pressure at the end of the duct was approximately 30 Pa and the air exit velocity at the end opening was approximately 5 m/s. A photos-tachometer was used to check the fan speed. Velocity profiles and static pressures were measured at eight locations along the length of the duct. These were spaced at 750-mm intervals, starting 4300 mm from the fan. Each velocity profile consisted of a 25 point Log-Tchebysheff traverse (Ower and Parkhurst 1977). Velocities measured at each point were weighted equally, as described by Eq.5:

\[ V_{ave} = \sum_{i=1}^{25} V_i/25 \tag{5} \]

where:
\[ V_{ave} = \text{average duct velocity (m/s)}, \]
\[ V_i = \text{velocity at point i (m/s)}. \]

A hotwire anemometer (Velocicalc, Model 8350, TSI, St. Paul, MN) was used to measure the air speeds. The velocity meter had a rated accuracy of ± 2.5% of reading and was calibrated for sea level (101.3 kPa) and a temperature of 21.1°C. Therefore, Eq. 6 was used to correct the measured velocities.

\[ V_{act} = V_m (273 + T_m)/(273 + 21.1)(101.3)/P_m \tag{6} \]

where:
\[ V_{act} = \text{actual velocity (m/s)}, \]
\[ V_m = \text{measured velocity (m/s)}, \]
\[ T_m = \text{measured temperature (°C)}, \]
\[ P_m = \text{atmospheric pressure in laboratory (kPa)}. \]

The room temperature was 21.1°C and the atmospheric
pressure was 93.77 kPa. The pressure taps, located adjacent to the velocity profile measuring points, were constructed by drilling a 1.6-mm hole through the top face of the duct. A 6.5-mm plastic tube was then countersunk into the pressure tap. The edge of the plastic tubing was sealed flush with the plywood duct with a silicon adhesive. The plastic tubing was connected to a micromanometer (Microtocter, Dwyer Instruments Inc., Michigan City, IN) which measured the static pressure to 0.25 Pa.

The air speed of the jet from each opening was measured by locating a 500-mm long plastic tube downstream from the opening. The air velocity probe was inserted into the centre of the tube to measure the centre line velocity. The tubes had inside diameters of 38 and 56 mm for the 25-mm and 50-mm openings, respectively. Equation 4 related these velocities to airflow rate from the fan. The values of K used in Eq. 4 were 1.27 and 1.25 for the 38 and 56-mm tubes, respectively.

RESULTS

Measured values of mean duct velocity, $V_d$, static pressure, $P_o$, and tube centre line velocity, $V_c$, are plotted against distance along the duct in Figs. 3, 4, and 5, respectively. Least-squares linear regression analyses were carried out on these data and the regression coefficients ($R^2$ values) are presented in Table I. The regression coefficients ranged from 0.91 to 0.99. The linear correlation between duct velocity and distance from the first opening was the highest while those between opening velocity and distance and between static pressure and distance were lower (Table I). The regression lines for duct velocity, static pressure, and opening velocity are also plotted in Figs. 3, 4, and 5, for the plywood and metal ducts, respectively.

The linear regression equations were used to obtain values of $V_d$ and $P_o$ that could be substituted into Eq. 3 to obtain values of $C_d$. These calculated $C_d$ values are plotted as a function of distance along the duct in Fig. 6.

To check the measurements of $V_c$, the measured opening velocity values were substituted into Eq. 4 to obtain values of total flow, $Q_t$. These were compared with flow rates determined from in-duct velocity measurements immediately downstream from the fan. The comparison of these values is shown in Table II. The flowrates from the individual openings derived from Eq. 4 are plotted against distance along the duct in Fig. 7.

DISCUSSION

The graphs in Figs. 3, 4, and 5, together with the regression coefficients provided in Table I, indicate that duct velocity, static pressure, and tube centre line velocity all varied linearly with distance along the duct. Figure 5 shows that the exit velocity was higher for the 25-mm openings than for the 50-mm openings even though the total area of openings was the same. This is explained by the fact that the total vena contracta area would be less for the smaller openings.

As shown in Fig. 6, the discharge coefficients varied linearly along the duct with mean values for the metal, 50-mm and 25-mm plywood openings of 0.70, 0.72 and 0.71, respectively. The metal openings had a lower $C_d$ value because the sharp-edged orifice caused more abrupt expansion of flow.

**Table I. Regression coefficients ($R^2$) for the experimental data**

<table>
<thead>
<tr>
<th>Material</th>
<th>Duct air velocity</th>
<th>Opening air velocity</th>
<th>Static pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal (55mm)</td>
<td>0.99</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td>Plywood (50mm)</td>
<td>0.99</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>Plywood (25mm)</td>
<td>0.99</td>
<td>0.91</td>
<td>0.93</td>
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</table>
Fig. 6. Discharge coefficient profile for metal and plywood openings.

Table II. Air flow rates and static pressures

<table>
<thead>
<tr>
<th>Material type</th>
<th>Outlet size (mm)</th>
<th>Run #</th>
<th>Recirculation rate (m³/s)</th>
<th>Pressure (Pa)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Measured</td>
<td>Predicted</td>
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<tr>
<td>Metal</td>
<td>50</td>
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<td>0.38</td>
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<td></td>
<td></td>
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<td>0.38</td>
</tr>
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<td>0.37</td>
<td>0.37</td>
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<tr>
<td>Plywood</td>
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Table III. Discharge coefficients

<table>
<thead>
<tr>
<th>Material</th>
<th>Outlet size (mm)</th>
<th>Run #</th>
<th>Discharge coefficient</th>
<th>Iterative procedure²</th>
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<tr>
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<td>Experimental value¹</td>
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<tr>
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<td></td>
<td>3</td>
<td>0.73</td>
<td>0.74</td>
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<tr>
<td>Plywood</td>
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<tr>
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<td>0.71</td>
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</tr>
</tbody>
</table>

¹ From Eq. 3.
² Saunders and Albright (1990)

Fig. 7. Opening airflow rate profile for metal and plywood openings (Eq. 1).

and higher losses. Figure 6 shows that the $C_d$ gradients for the metal, 25-mm and 50-mm plywood openings along the duct have similar negative slopes. The $C_d$ values changed by about 0.08 between the first opening and the last (0.013/m). In terms of losses, the most effective configuration was the plywood wall with 50-mm openings while the least effective were those in the metal wall. The reason for the decrease in $C_d$ could be due to the change in exit angle of the air jets along the duct.

An iterative procedure developed by Saunders and Albright (1984) uses the static pressure at the last opening and the fan output to arrive at a mean $C_d$ value for the openings such that the predicted recirculation rate is the same as that measured. Table III shows that the mean $C_d$ values calculated using this procedure agreed very well with those calculated by Eq. 3.

The comparison of predicted and measured values presented in Table II indicates good agreement for the 50-mm discharge openings in metal and plywood. The agreement is poorer for the plywood duct with 25-mm holes. In the latter case, total airflow rate calculated from the sum of opening
discharge rates was consistently higher than that measured in the duct. The reasons for this discrepancy are not clear but could be due to different flow or entry conditions arising from the smaller holes. In this case, a different ratio of centre line velocity to mean velocity might have been more appropriate than the value of 1.25 used in calculating the individual discharge rates.

The change in $C_d$ values illustrated in Fig. 6 and the change in exit velocities (Fig. 5) along the length of the duct suggest that the airflow from the openings increases along the length of the duct. However, Fig. 7 shows that the distribution of air flow from the openings is uniform along the duct length. As the static pressures and exit velocities increase towards the end of the duct, the $C_d$ value decreases yielding a constant airflow from each opening along the length of the duct.

CONCLUSIONS

The following conclusions were drawn from the project results:

1. The mean discharge coefficients for 50-mm diameter openings in metal, 50-mm and 25-mm openings in plywood were 0.70, 0.72 and 0.71, respectively for an exit velocity of 5 m/s. For each type of opening the $C_d$ values decreased by about 0.0133 per meter of duct.

2. The increase in static pressure and decrease in the $C_d$ values along the length of duct resulted in a uniform distribution of airflow along the duct.

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REFERENCES


