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ABSTRACT

A full scale physical model eave opening and baffled slot inlet system for a mechanically ventilated livestock building was tested to determine the effect of pressure differences and attic opening size on air flow rates. Pressure differences were varied between the eave, attic and room of the model. Flow rates through the attic and the room, and corresponding pressure differences were measured to calculate loss coefficients.

Closed attic tests that prevented interactions between the inlet and attic were conducted to develop regression equations to predict the coefficient of discharge (C_d) and the loss coefficient (C_o). Linear regression equations fit the observed data very well and agreed with established theory. Open attic tests, with different sized attic openings, indicated that flow into the room was reduced compared to the closed attic case.

INTRODUCTION

Proper slot inlet design is important for good distribution and mixing of fresh incoming air in livestock buildings. Inlet sizing is critical for providing adquate inlet area and proper velocity for the required air flow through confinement buildings. Current design criteria are based primarily on research by Albright (1976) and Walton and Sprague (1951). Both developed relationships for flow rate based on static pressure difference and slot width using simplified slot inlet systems. Losses due to configuration of the flow path prior to the slot inlet were not investigated, nor were interactions with the attic plenum space.

Walton and Sprague (1951) used pressure differences approaching 78 Pa (0.3 in. H_2O) to account for the effects of a 11.2 m/s (25 mph) wind. Flow rates were evaluated by testing different slot widths at a variety of pressure differences. They developed the design criteria that a 25 mm (1 in.) slot at 10 Pa (0.04 in. H_2O) and 31 Pa (0.125 in. H_2O) allows air flow rates of 0.077 and 0.155 m^3/s per m (50 and 100 cfm/ft), respectively.

Albright (1976) tested hinged baffle slotted inlets that directed air down a wall or across a ceiling. Assuming the inlet configuration prior to the inlet opening did not significantly affect the air flow, he concluded that a discharge coefficient of 0.8 could be used with the Bernoulli equation when air is directed down the wall to calculate the flow rate within 5%.

Wilson et al. (1983) outlined an approach to inlet design using the Bernoulli equation assuming inviscid, incompressible fluid flow. The coefficient of discharge (C_d), defined in equation [1], was used to relate the actual flow rate with losses to the ideal flow rate. All terms are defined in the nomenclature.

$$\frac{Q_A}{L} = \frac{C_d Q_I}{L} = C_d W \left(\frac{2\Delta P}{\rho}\right)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots [1]$$

A variety of values for the coefficients of discharge were given including Albright's (1976) constant of 0.8. For flow directed across the ceiling, Wilson et al. (1983), MWPS, recommends that 0.6 should be used as a design value to account for vena contracta.

American Society of Heating, Refrigerating and Air Conditioning Engineers (1981), ASHRAE, outlines another procedure to describe flow through inlets using the Bernoulli equation. This method defines a loss coefficient (C_o) as a function of total pressure loss and velocity pressure.

$$C_o = \frac{2\Delta P_t}{\rho V_o^2} = \frac{\Delta P_t}{P_{v,o}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

This coefficient is used in a piece-by-piece procedure for determining pressure losses with the aid of tables giving local loss coefficients for specific duct geometries.

The purposes of this study were to determine: the effects of the flow path prior to the slot inlet and the attic conditions on ventilation rates; and the relationships between flow rate, static pressure difference and width of slot opening. The attic conditions varied were the attic opening size and the pressure or vacuum in the attic relative to the eave. The attic opening size was varied to determine its affect on flow through the slot inlet into the room. The pressure or vacuum in the attic was varied to represent the effects of wind blowing through an attic and around a building.

APPARATUS AND PROCEDURES

A full scale model (1.12 m (44 in.) long) of the eave opening and slot inlet for a raised deck swine nursery was constructed (MWPS plan number 72604) (Fig. 1). The height of the model made the inlet baffle approximately 1 m (40 in.) from the floor. To enclose the nursery room portion of the model, a sidewall, 1.37 m (54 in.) from the inlet, and endwalls were added. The inlet baffle, hinged

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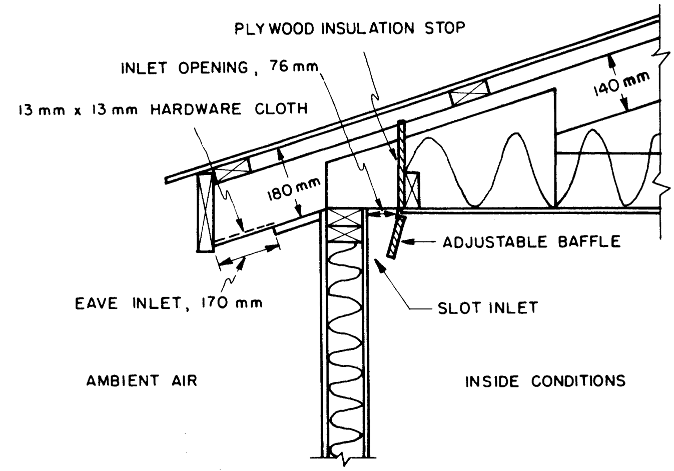

Fig. 1—Slotted eave inlet construction details. (Not drawn to scale).

to send air down the wall, was adjustable and held securely using turnbuckles. Duct tape sealed the crack along the hinge. A removable plywood stop was installed to partially or completely close off the opening to the attic. One endwall of the model was removable to install different sized stops. The stops were made to allow openings of 76 mm (3.0 in.), 38 mm (1.5 in.), 19 mm (0.75 in.) and closed.

The model was coupled with a fan testing unit constructed by Person et al. (1979) according to Air Movement and Control Association (1974), AMCA, standard 210 specifications (Fig. 2). The eave opening was placed in the fan testing unit where a fan being tested would normally be installed. The fan test unit was chosen because flow rates could be accurately measured and adjusted. The pressure in the fan test unit at the eave was used as the "outside" pressure.

Using International Standards Orgainzation (1983) and American Society of Mechanical Engineering (1959) procedures, orifice plates were sized to measure flow rates through the room and attic to within 1%. Two 152 mm (6 in.) PVC pipes, side by side, were connected to the attic portion of the building unit. These had 95 mm (3.75 in.) orifice plates set up with D and D/2 pressure tap placement. One pipe measured flow into the attic and the other air flow out of the attic. Only one pipe was used for each test with the other sealed when not in use. These two pipes were then connected to a plenum box equipped with a sliding door and two fans. This allowed for adjustment of the attic pressure by changing the plenum box pressure.

Another pipe was installed to measure air leaving the room portion of the model. This orifice plate was 102 mm (4.02 in.) in diameter and exited to ambient conditions. A slide was installed to restrict the flow to

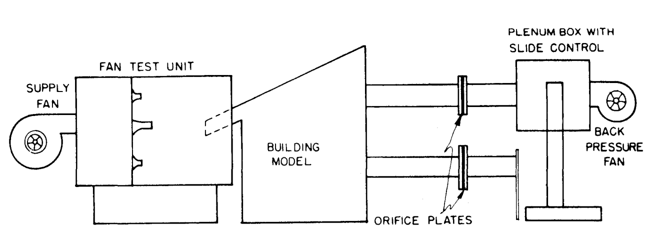

Fig. 2—Components of the experimental unit. (Not drawn to scale).

increase the room pressure when the pressure difference between the outside and the room became too large.

U-tube manometers (± 12.4 Pa), were used to measure the pressure drops across the orifice plates. Inclined manometers (± 1.2 Pa), were used to measure the difference between outside and inside static pressures and between attic and outside static pressures. Pressure lines were connected to the model perpendicular to the flow direction, flush with the wall surface and away from the incoming jets of air.

Two experimental set-ups were used. The closed attic case, closed the opening which allowed air flow through the attic. The second set-up called the open attic case permitted different size openings to the attic and a variety of outside-to-attic pressure differences. It was assumed, that air was incompressible, there were no significant buoyancy effects, and the model behaved as an infinitely long slot. The aspect ratios for the 10, 25 and 30 mm (0.39, 1.0, 1.18 in.) inlet widths exceeded 24 which is recommended for neglecting edge effects (Albright, 1976). The aspect ratio for the 50 mm (1.97 in.) inlet width was only 22, but edge effects were still assumed negligible.

The closed attic case measured pressure losses experienced by air flowing through the eave opening and the baffled inlet. No air was allowed to flow into the attic. The adjustable inlet baffle was set at one of four widths: 10, 25, 30, 50 mm (0.39, 1.0, 1.18, 1.97 in.) and the outside-to-inside pressure difference was set at four levels: 10, 15, 20, 31 Pa (0.04, 0.06, 0.08, 0.125 in. H_2O), in a randomized fashion. The specified pressure difference was obtained by adjusting the flow through the fan test unit. The flow rate and static pressure difference were measured and replicated for statistical accuracy.

The open attic case had three different sized openings to the attic: 76, 38, 19 mm (3.0, 1.5, 0.75 in.). At each of these attic openings, 7 static pressure differences between the outside and attic pressure were induced. The attic pressure was 30, 20, 10, 0, −10, −20 and −30 Pa relative to the outside pressure. Flow rates through the attic and the room were measured along with the appropriate pressures. The baffled slot inlet was set to 25 mm (1.0 in.) for the entire open attic case to eliminate variations due to inlet width. Outside pressure was always maintained above inside pressure and within the normal operating range of a negative pressure ventilated livestock building. Further details are given in Harmon (1986).

RESULTS AND DISCUSSION

The definitions of the discharge coefficient (C_d) and the loss coefficient (C_o) in equations [1] and [2] appear very different. However, upon close inspection, it may be observed that:

$$C_o = 1/C_d^2 \quad \text{[3]}$$

Therefore, C_o is a transformation of C_d. This is a useful relationship for ventilation design of agricultural buildings because ASHRAE can be an additional source of coefficients.

TABLE 1. MEAN AND STANDARD DEVIATION OF LOSS COEFFICIENT (C_o) FOR THE CLOSED ATTIC CONFIGURATION

Pressure difference, Pa	Slotted inlet width, mm				
	10	25	30	50	All
10	1.213 (0.000)	1.623 –	1.684 (0.086)	2.412 (0.063)	1.749 (0.498)
15	1.076 (0.212)	1.641 (0.154)	1.716 (0.121)	2.382 (0.042)	1.704 (0.507)
20	1.113 (0.171)	1.683 (0.062)	1.701 (0.088)	2.465 (0.066)	1.741 (0.520)
31	1.047 (0.097)	1.586 (0.034)	1.712 (0.066)	2.434 (0.000)	1.695 (0.531)
All	1.112 (0.128)	1.634 (0.080)	1.703 (0.071)	2.423 (0.050)	1.721 (0.489)

Cell contents: C_o mean (standard deviation)

TABLE 2. MEAN AND STANDARD DEVIATION OF DISCHARGE COEFFICIENT (C_d) FOR THE CLOSED ATTIC CONFIGURATION

Pressure difference, Pa	Slotted inlet width, mm				
	10	25	30	50	All
10	0.908 (0.000)	0.785 –	0.771 (0.020)	0.644 (0.008)	0.776 (0.108)
15	0.971 (0.096)	0.782 (0.037)	0.764 (0.027)	0.648 (0.006)	0.791 (0.130)
20	0.952 (0.073)	0.771 (0.014)	0.767 (0.020)	0.637 (0.008)	0.782 (0.123)
31	0.979 (0.045)	0.794 (0.008)	0.765 (0.015)	0.641 (0.000)	0.795 (0.130)
All	0.953 (0.057)	0.783 (0.019)	0.767 (0.016)	0.642 (0.007)	0.786 (0.118)

Cell contents: C_d mean (standard deviation)

Closed Attic

Table 1 summarizes C_o values calculated from the observed data using equations [1] and [3]. A regression performed on C_o values indicated that they were independent of static pressure difference. A regression including both the width of the slotted inlet and outside-to-inside static pressure difference showed no improvement over a regression on width only.

$$C_o = 0.776 + 0.0326\, W_s \quad \ldots\ldots\ldots\ldots [4]$$

$$r^2 = 0.967$$

Overall C_o's were also estimated using local C_o's found in ASHRAE (1981), measured flow rates and the sum of the calculated pressure drops through each component. Local C_o's for an entrance with a screen, two 90 deg mitered elbows, and an exit, based on the geometric shape and dimensions of the physical model, were selected. Results indicated that the elbows contributed very little to the total pressure loss. Once the local loss coefficients were obtained, equation [2] was used to find the pressure loss of each component. These pressure losses were added together and, using measured flow rates, inserted into equation [2] to find the overall C_o. The results indicated that a large portion of the total pressure loss was contributed by the baffled inlet. In addition these coefficients were independent of outside-to-inside pressure differences and remained constant for each slotted inlet width.

The regression line (equation [4]), the ASHRAE values and values from the Albright (1976) experiment converted to C_o (equation [3]) are shown in Fig. 3. The results indicate that the ASHRAE method was fairly accurate for narrow openings, but increasingly underpredicted the overall C_o as the inlet width increases.

Using the same measured data, C_d's were calculated using equation [1] and tabulated in Table 2. Equation [5] is the resulting regression equation.

$$C_d = 1.01 - 0.0076\, W_s \quad \ldots\ldots\ldots\ldots [5]$$

$$r^2 = 0.902$$

A comparison of Albright's (1976) data, the converted ASHRAE values, and the C_d regression line (equation [5]) may be seen in Fig. 4. Albright (1976) stated that the use of a constant C_d value of 0.8 would allow computing flow rates to within 5%. The converted ASHRAE values and equation [5] indicate that C_d values are negatively related to slot width.

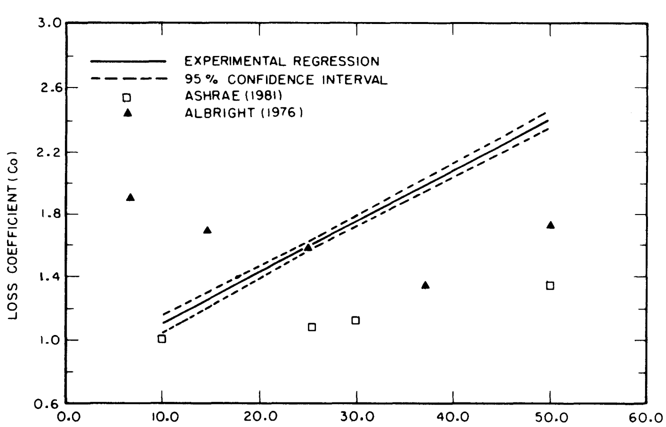

Fig. 3—Comparison of the C_o regression line to ASHRAE values and converted Albright (1976) values.

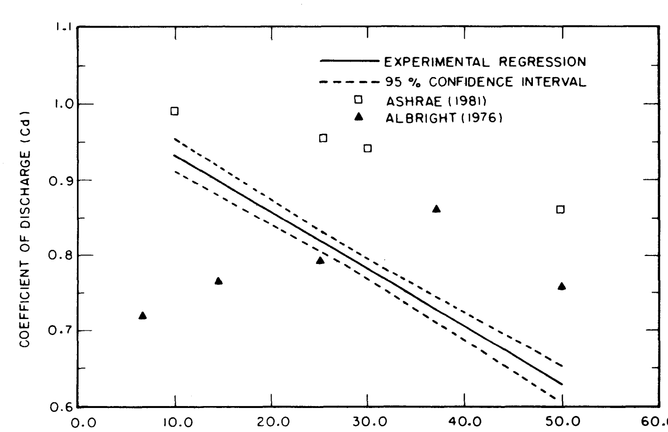

Fig. 4—Comparison of the C_d regression line to Albright (1976) values and converted ASHRAE values.

TABLE 3. MEAN AND STANDARD DEVIATION OF FLOW RATE ($m^3/s\text{-}m$) FOR THE CLOSED ATTIC CONFIGURATION

Pressure difference, Pa	Slotted inlet width, mm				
	10	25	30	50	All
10	0.038 (0.000)	0.083 —	0.097 (0.002)	0.135 (0.002)	0.089 (0.040)
15	0.049 (0.005)	0.101 (0.005)	0.117 (0.004)	0.166 (0.001)	0.109 (0.045)
20	0.056 (0.004)	0.115 (0.002)	0.135 (0.003)	0.188 (0.003)	0.124 (0.051)
31	0.073 (0.003)	0.149 (0.001)	0.169 (0.003)	0.236 (0.000)	0.157 (0.062)
All	0.054 (0.014)	0.116 (0.025)	0.129 (0.029)	0.181 (0.039)	0.120 (0.054)

Cell contents: Q/L mean (standard deviation)

The flow rates through the room are given in Table 3. During statistical analysis, slot width and static pressure difference were found to have an interactive relationship. A regression model was chosen which was similar to the theoretical equation [1].

$$Q/L = 0.0243 + 0.000771\ W_s(\Delta P_{O-I})^{0.5} \quad \ldots\ldots\ldots [6]$$

$$r^2 = 0.975$$

Theoretically, the intercept of equation [6] should be zero since a closed inlet or no pressure difference should yield no flow. Statistically the non-zero intercept was significant at the 5% level. The room flow tube had a measuring accuracy of $\pm$ 2.2% which could account for the difference in the intercept as well as the slope of equation [6].

Selecting $W_S(\Delta P)^{0.5}$ as the regression variable means that $C_d(2/\rho)^{0.5}/1000$ corresponds to the slope in the theoretical equation [1]. When this slope was calculated using the data taken in this study, values generally fell in the range between 0.0008 and 0.0012. These are greater than the value 0.000771 in equation [6].

Fig. 5 illustrates the regression line (equation [6]) compared with Walton and Sprague (1951). The line and points appear concurrent over the range of the line, but extrapolating, the line falls below the Walton and Sprague (1951) points. The effect of the upstream configuration flow through the eave opening and over the wall (Fig. 1) may account for this reduced flow rate.

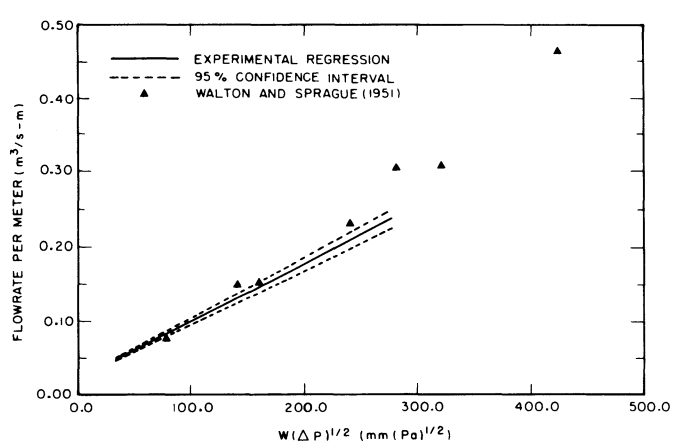

Fig. 5—Flow rate regression line compared to Walton and Sprague (1951) for the closed attic test.

Open Attic

The plywood used to block off the attic was removed from the model and replaced with plywood sheets which allowed either a 76, 38 or 19 mm (3.0, 1.5, 0.75 in.) opening to the attic.

When the first attic opening of 76 mm (3.0 in.) was tried, no pressure or vacuum could be created in the attic. When the back pressure fan and plenum were adjusted to create a pressure or vacuum in the attic, the outside pressure (pressure within the fan testing unit) concurrently changed. The opening was then changed to 38 mm (1.5 in.). Pressure could be induced in the attic to a level of 10 Pa (0.04 in. H_2O) above outside. Vacuum levels to -30 Pa (0.12 in. H_2O) could be created below outside pressure. The 19 mm (0.75 in.) opening allowed pressure and vacuum to be set at the seven desired levels from 30 Pa to −30 Pa (0.12 in. to −0.12 in. H_2O).

The loss coefficient, C_o, was calculated from the data using equations [1] and [3]. Table [4] presents the mean and standard deviations of C_o and the flow rate, Q_I, for the different treatments. Analyses of variance were conducted on C_o and Q_I to determine the significance of the effects of the attic opening width, W_A, and the outside to attic pressure difference ($\Delta P_{0\text{-}A}$. The Q_I ANOVA results show that Q_I was independent of W_A and $\Delta P_{0\text{-}A}$ at the 0.05 level.

The results indicate that C_o was dependent on $\Delta P_{0\text{-}A}$ and independent of W_A at the 0.05 level. Tests on the regression of C_o based on W_A and $\Delta P_{0\text{-}A}$ indicated a non-

TABLE 4. MEAN AND STANDARD DEVIATION OF LOSS COEFFICIENT (C_O) AND FLOW RATE (Q_I) ($m^3/s\text{-}m$)

Pressure difference $\Delta P_{0\text{-}A}$, Pa	Loss coefficient		Flow rate	
	Attic opening, mm		Attic opening, mm	
	19	38	19	38
-30	5.60 (2.10)	— —	0.059 (0.013)	— —
-20	4.12 (2.20)	— —	0.074 (0.018)	— —
-10	2.55 (0.27)	5.44 (2.90)	0.060 (0.009)	0.053 (0.021)
0	3.71 (0.49)	2.85 (1.01)	0.068 (0.003)	0.064 (0.007)
10	1.70 (0.42)	2.58 (1.09)	0.073 (0.018)	0.059 (0.012)
20	2.32 (0.84)	3.56 (1.09)	0.065 (0.009)	0.071 (0.002)
30	2.66 (1.23)	4.21 (0.67)	0.055 (0.010)	0.067 (0.004)
All	3.09 (1.57)	3.37 (1.70)	0.066 (0.013)	0.061 (0.012)

Cell contents: Mean (standard deviation)

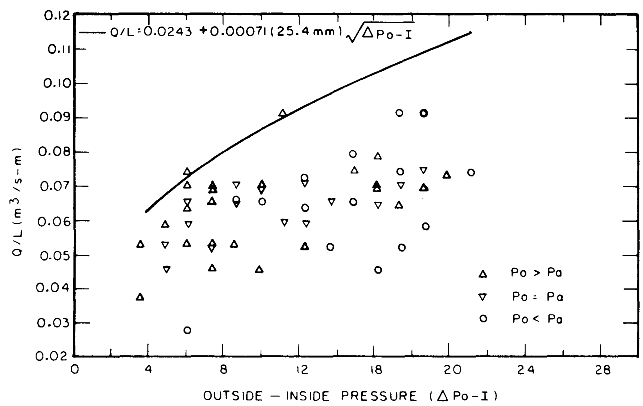

Fig. 6—Comparison of the closed attic regression for flow rate, equation [6] and the open attic data.

constant variance, (Cook and Weisberg, 1983), which made the regression inappropriate. A transformation of the data to ln C_o gave a constant variance but yielded a model of poor correlation.

Open vs. Closed

A comparison between the results from the open and closed attic tests was done to illustrate the change in ventilation capacity that attic pressure or vacuum and attic opening size made. Fig. 6 shows the regression line for Q_I/L plotted against $\Delta P_{0\text{-}I}$ from the closed attic experiment, equation [6]. A slot width of 25 mm was used for the closed attic regression line to match the open attic experiment which had a 25 mm slot inlet width. The open attic data points in the figure for the positive, negative, and zero $\Delta P_{0\text{-}I}$ values were plotted using different symbols. The open attic points were scattered so that no single category appears to be vastly different.

The open attic points in Fig. 6 were well below the closed attic line. A statistical test to see if the line and the points were from the same model was done (Weisberg, 1980). At the 0.05 level, the closed and open attic did not belong in one regression, indicating that the two configurations performed differently. Even when no pressure difference between the outside and the attic existed, a lower flow rate was achieved in the open attic case at all $\Delta P_{0\text{-}I}$, than was achieved in the closed attic configuration. All open attic data points lie below the regression line for the closed attic configuration, showing that flow rates were reduced just because of the opening into the attic.

CONCLUSIONS

Inlet design and management are important because they affect the ventilation rate, air distribution and mixing in negative pressure mechanically ventilated buildings. This study was conducted to determine the relationship between flow rate, static pressure difference and slot opening width for a down-the-wall eave inlet system. The study also considered the effect of the attic opening on the ventilation rate.

The following conclusions were made from this study:

1. Discharge and loss coefficients for slot inlets with a closed attic configuration depend on slot width.
2. The flow rate per unit length for slot inlets with a closed attic configuration was reliably modeled using $W_S(\Delta P)^{0.5}$. Regression coefficients were similar to theoretical values.
3. For the open attic configuration, C_o and Q_I were not found to be dependent on $\Delta P_{0\text{-}A}$ and the attic opening size which ranged between 19 and 76 mm.
4. Reduced flow rates through the inside of the building were observed for the open attic configuration compared to the closed attic configuration.

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Nomenclature

C_d	coefficient of discharge, dimensionless
C_o	loss coefficient, dimensionless
D	diameter, m
$P_{v,o}$	dynamic pressure at section 0, Pa
Q/L	flow rate into the building per unit length, m^3/s-m
Q_A	flow rate through the attic, m^3/s
Q_I	flow rate through the inside of the building, m^3/s
Q_A/L	actual flow rate per unit length, m^3/s-m
Q_I/L	ideal flow rate per unit length, m^3/s-m
V_o	mean velocity at section 0, m/s
W	slot width, m
W_A	attic opening width, mm
W_S	inlet slot width, mm
ΔP	outside-to-inside static pressure difference, Pa
$\Delta P_{0\text{-}A}$	outside minus attic static pressure difference, Pa
$\Delta P_{0\text{-}I}$	outside minus inside static pressure difference, Pa
ΔP_T	total losses of a fitting as total pressure, Pa
ρ	density of air, kg/m^3