Evaluation of methods to measure the performance of perforated ventilation ducts

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El Moueddeb, K., Barrington, S.F. and Newman, B.G. 1996. **Evaluation of methods to measure the performance of perforated ventilation ducts**. Can. Agric. Eng. **38**:207-213. To determine the most accurate procedure to monitor the air distribution pattern of perforated ventilation ducts, methods were compared for the experimental measurement of duct static air pressure and outlet air flow. Static air pressure readings, using a pitot static tube and piezometric wall taps, were compared for a rectangular perforated wooden ventilation duct with a length to hydraulic diameter ratio (L/D_h) of 21.85 and 14 outlets giving an aperture ratio of 0.5. All readings were identical except for those measured over 25% of the duct length near the fan end, as they were exposed to air swirling and showed a coefficient of variation as high as 5.2%. Thus, the pitot static tube and piezometer wall taps will give the same air static pressure readings if, between the fan and the perforated duct, a non perforated section is added and its length is 10 times the duct's hydraulic diameter. The air flow at each outlet was measured using the grid method applied to both the outlet surface itself and the inside duct cross section, upstream and downstream from each outlet. Because the true outlet air flow equals the product of the air jet velocity component perpendicular to the surface and the flow area, a new instrument was developed to simultaneously measure the outlet air jet discharge angle and velocity. The outlet air flow measurements were performed using 4 rectangular perforated ducts with L/D_h of 18.8 and 12 outlets giving, respectively, aperture ratios of 0.5, 1, 1.5, and 2. As compared to measurements taken inside the perforated duct, those obtained at the outlet surface predicted the outlet air flow with an error of 3 to 28%, for aperture ratios of 0.5 to 2, respectively. This error was due to the contraction of the outlet air jet which was too small to be measured accurately.

Les méthodes expérimentales pouvant mesurer la pression statique de l'air à l'intérieur de conduits perforés de ventilation et le débit d'air des perforations furent comparées pour déterminer leur précision. Un tube de pitot et des troues piézométriques furent utilisés pour mesurer la pression statique de l'air à l'intérieur d'un conduit de bois perforé et rectangulaire avec un rapport de longueur au diamètre hydraulique (L/D_h) de 21.9 et un rapport d'aperture de 0.5. Les deux instruments mesuraient des valeurs identiques sauf sur 25% de la longueur du conduit à partir du ventilateur où le coefficient de variation des lectures atteignait 5% à cause des perturbations dans l'écoulement. La pression statique à l'intérieur de conduits perforés peut donc être mesurée avec précision par les deux instruments si, entre le ventilateur et le conduit perforé, on installe une section non perforée de longueur égale à dix fois le diamètre du ventilateur. Le débit d'air à chaque perforation fut mesuré par la méthode de la grille appliquée à la surface de perforation elle-même et à la surface intérieur du conduits, en amont et en aval de chaque perforation. Parce que le vrai débit d'air d'un orifice est mesuré à partir de la vitesse perpendiculaire à l'aire d'écoulement, un appareil fut développé pour mesurer simultanément l'angle et la vitesse du jet d'air s'échappant des perforations. Des mesures de vélocité d'air furent prises à même 4 conduits dont le L/Dh était de 18.8 et le rapport d'aperture était de 0.5, 1, 1.5 et 2, respectivement. Comparativement aux lectures prises à l'intérieur du conduit, le débit d'air des perforations, mesuré à leur surface, donnait une erreur de 3 à 28% pour un rapport d'aperture de 0.5 à 2.0, respectivement. Cette erreur était associée à la contraction du jet d'air qui était trop étroite pour être mesurée avec précision.

INTRODUCTION

Perforated ventilation or recirculating ducts are used in the environmental control of livestock and poultry buildings as well as for the conditioning of agricultural produce. These systems are preferred for the heating and cooling of air spaces because of their efficiency in blending fresh air into the animal space with minimum drafts.

The air distribution pattern of these perforated ducts is complicated by the inter-relation of several factors such as construction material and friction effects, fan capacity against pressure head, outlet size and spacing, and perforated duct length and cross-sectional area. Recent developments in the science of ventilation require the improvement of the design of perforated ducts to predict, for example, air velocity at the outlets since this affects air velocity at the floor of the ventilated room and hence the level of comfort of the animals housed (Ogilvie et al. 1990). This design problem can be solved with exact fluid mechanics models refined through the testing of hypotheses and the elimination or simplification of terms. Consequently, fluid mechanics parameters of experimental, perforated ventilation ducts must be measured accurately.

To measure static air pressure inside ducts (Table I), Bailey (1975) and Saunders and Albright (1984) used piezometric wall taps, while Carpenter (1972) and Brundrett and Vermes (1987) used pitot-static tubes. A pitot-static tube can detect both the static and the total air pressure while the wall tap can only detect static air pressure. The wall tap avoids errors stemming from the misalignment of the pitot-static tube but its attachment to thin flexible walls, such as those of polyethylene, can be difficult. With such perforated ducts, static air pressure is best obtained with a static tube inserted inside the perforated duct. For non-perforated pipes with a smooth inside surface, these two devices are known to measure the same static air pressure at any cross section (Streeter and Wylie 1981) whereas, they have not been compared for perforated ventilation ducts with equally spaced outlets.

Table I: Perforated duct parameter measurement

Author	Duct	Measurement methods: Parameter	Equipment	Method
Bailey (1975)	Perforated polyethylene duct	Discharge angle	Vane anemometer + protractor	In arc above the outlet
		Discharge velocity	Static tube	6 - point log-linear method
		Static pressure	Piezometric opening	Flush tap
Carpenter (1972)	Perforated polyethylene duct	Discharge velocity	Vane anemometer	No angle measurement
		Static pressure	Static tube	Centre of cross-section
Barrington and MacKinnon (1990)	Perforated wooden duct	Outlet velocity	Compuflow thermo-anemometer	Traverse method
		Static pressure	Piezometric opening	Outstanding tap
Saunders and Albright (1984)	Perforated polyethylene duct	Outlet velocity	Pitot tube	At centre of outlet
		Static pressure	Piezometric opening	Flush tap
Brundrett and Vermes (1987)	Perforated polyethylene duct	Outlet velocity and angle	Pitot tube	Protractor + yarn tellate
		Static pressure	Pitot tube	-
Patsula et al. (1991)	Perforated wooden or metal duct	Outlet velocity	Hotwire anemometer	No angle measurement
		Static Pressure	Piezometric openings	Flush pressure taps

Similarly, several methods have been used to measure air velocity and discharge angle at the outlets of perforated ventilation ducts. Often, the discharge angle is not considered (Carpenter 1972; Saunders and Albright 1984) but the true flow across an area is the product of the area and the velocity component perpendicular to that area. This is of importance since the outlet air jet angle varies along the length of perforated ducts (Koestel and Tuve 1948).

The work described here had three objectives. The first was to compare static air pressure readings using the static tube and piezometric taps in order to establish which method is most appropriate for perforated ventilation ducts. The second was to adapt and test an instrument to simultaneously measure both the outlet air jet angle and velocity. The third was to find an accurate method of measuring outlet air flow. Thus, the grid method was applied in two ways; one across the inside section of the duct, upstream and downstream from each outlet; and another outside the duct across the outlet area. As described by Burgess et al. (1989), the grid method requires that the rectangular flow area be divided into equal areas and that measurements be taken at the centre of these equal areas and parallel to the flow.

MATERIALS AND METHODS

Measurement of perforated duct static air pressure

To measure duct air static pressure, the static tube and the piezometric taps were compared using a wooden perforated duct built of frame members, 39 mm by 39 mm, covered with 6 mm thick presswood panelling (Fig. 1). The duct offered an inside net cross-sectional area of 0.173 m^2 (597 mm by 292 mm less 4 times 39 mm x 39 mm) and was perforated on both sides at every 610 mm over a length of 8.5 m by 14 pairs of rectangular outlets (125 mm by 25 mm) located at the mid height of the side panels. The first pair of outlets was 440 mm from the closed end of the duct. The duct sections were sealed using caulking compound. The 450 mm axial duct fan (ACME EJF 18F-V, ACME Engineering & Manufacturing Corp., Muskogie, OK) had a 0.25 kW motor running at 1600 rpm and an air straightener (Fig. 2). An 1800 mm long tapered section was used to fit the fan onto the perforated duct and to reduce swirling at the first outlets (Fig. 1).

A vertical micro-manometer (Microtector® Gage, Dwyer Instruments, Inc., Michigan City, IN) with an accuracy of ± 0.062 Pa was used in both instances to read static air pressure. To insert the static tube or the wall piezometric taps, small holes were drilled along the centre line of the top panel

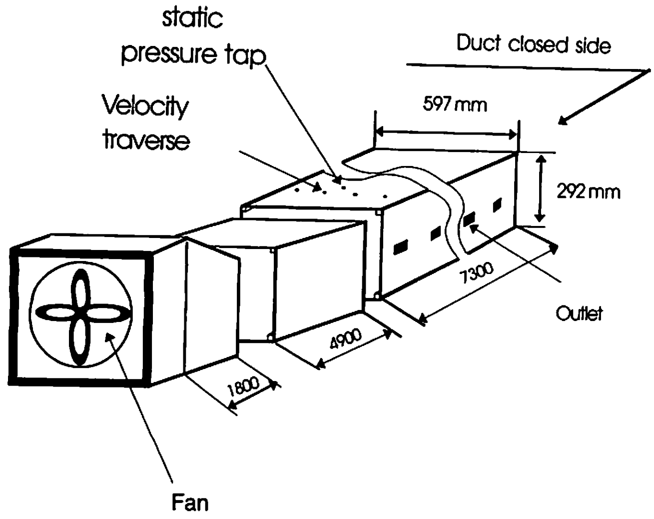

Fig. 1. A three dimensional view of the ventilation duct.

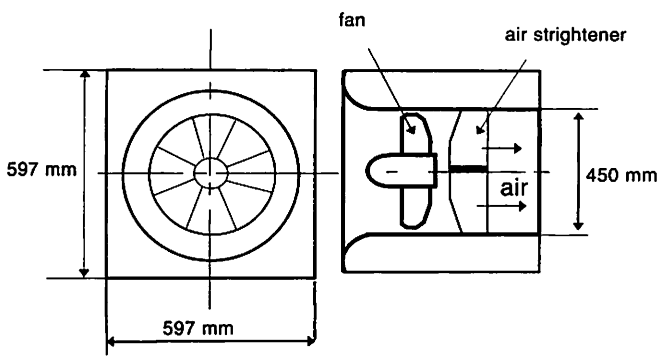

Fig. 2. The frame of the fan inside the duct.

of the perforated duct, half way between each two pairs of outlets for a total of twelve such holes. For both instruments, static air pressure measurements were repeated seven times before moving to the next hole. All the measurements were taken under the same air conditions and fan setting.

Using the static tube, perforated duct static air pressure was measured at depths of 50, 100, 150, 250, and 290 mm from the top panel at the 12 locations along the length of the perforated duct. At the same 12 locations, the measurements were repeated using both a piezometric tap inserted into the top panel and a static tube inserted at the centre of the cross-section of the perforated duct. Both instruments were connected to the micro-manometer. For both tests, Duncan's New Multiple Range Test, at a 95% confidence level and a completely randomized design (Steel and Torrie 1986), were used to identify any significant difference in pressure measurement at each of the 12 locations. For the first and second experiments, the treatments were depth from the top panel and static air measurement instrument, respectively.

Measurement of outlet air flow

Outlet air flow is obtained from the product of a flow area surface and the velocity component perpendicular to this area:

$$q_o = (A_o/n)\sum_{i=1}^{n} V_{oi} \sin(\alpha_i) \qquad (1)$$

where:

q_o = air flow from one outlet (m^3/s),
A_o = outlet area (m^2),
n = number of grid areas over the air flow cross section,
V_{oi} = i^{th} grid area air outlet velocity (m/s), and
α_i = i^{th} grid area air outlet angle (degrees).

Inside the perforated duct, outlet flow can be obtained from the difference in duct flow upstream and downstream from the outlet (Fig. 3):

$$q_o = (A/n)\sum_{i=1}^{n} V_{iu} - (A/n)\sum_{i=1}^{n} V_{id} \qquad (2)$$

where:

A = perforated duct cross sectional area (m^2),
V_{iu} = air velocity inside perforated duct upstream from i^{th} outlet and summed from the grid measurements (m/s), and
V_{id} = air velocity inside perforated duct downstream from i^{th} outlet and summed from the grid measurements (m/s).

A 7.3 m wooden perforated duct structure (Fig. 1, Table II) was built of interchangeable side panels with 12 pairs of outlets spaced at 610 mm located at mid-height and giving aperture ratios of 0.5, 1.0, 1.5, and 2.0. A nonperforated section of 4.9 m was installed between the tapered fan transition section and the perforated duct sections to reduce air swirling at the outlets nearest to the fan end.

Using the grid method (Burgess et al. 1989), outlet air flow was initially determined from the difference in air flow

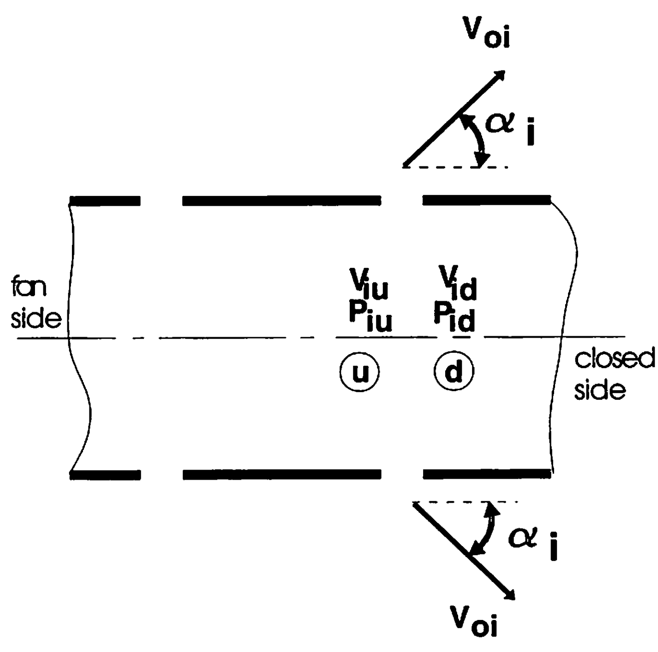

Fig. 3. The outlet air jet angle.

Table II: Characteristics of the experimental perforated ducts used for outlet air flow measurement

Duct	Outlet size (mm x mm)	Aperture ratio*
1	145 x 25	0.5
2	145 x 50	1.0
3	145 x 75	1.5
4	145 x 100	2.0

* The aperture ratio equals $\Sigma A_o/A$.

Note: the experimental duct used to test static pressure instruments had 14 pairs of outlets while the 4 experimental ducts used to test outlet flow measurement techniques had 12 pairs of outlets.

All ducts had a section of 7.3 m perforated by 12 outlets spaced at 610 mm.

across the inside section of the duct upstream and downstream from each pair of outlets (Eq. 2). The duct cross sectional area was divided into 16 equal sections and, for each section, the average air velocity was computed from 10 repeated measurements taken with a thermo-anemometer (Model 8500D-II, Alnor Instrument Company, Niles, IL) with an accuracy of 3% of the indicated reading over a range from 0.1 to 15 m/s.

Outlet air flow was then determined by applying the grid method to the outlet flows, outside the perforated duct. To simultaneously measure the outlet air jet discharge angle and velocity, a three-tube-pitot instrument was used (Fig. 4). Fixed on a mechanism allowing its rotation about a vertical axis facing the outlet, this instrument accounted for its orientation by means of a horizontal needle moving over a fixed protractor. By being connected to one port of a micro-manometer where the other port is left open to atmospheric pressure, the central tube of the three-tube-pitot instrument measured a relative pressure which can be converted to air velocity using Bernoulli's principle. The two exterior tubes of the instrument were connected to opposite ports of an identical micro-manometer and thus measured the outlet air direction when they registered the same dynamic pressure as the instrument was being slowly rotated about its vertical axis. This three-tube-pitot instrument was calibrated inside the low speed wind tunnel of the Mechanical Engineering Research Laboratory of McGill University and gave a pitot correction factor (real velocity/pitot tube velocity) of 0.992. It repeatedly measured air jet angles with an error of $\pm 2.5^o$. However, two persons were required to manipulate the instrument and to read the micrometers.

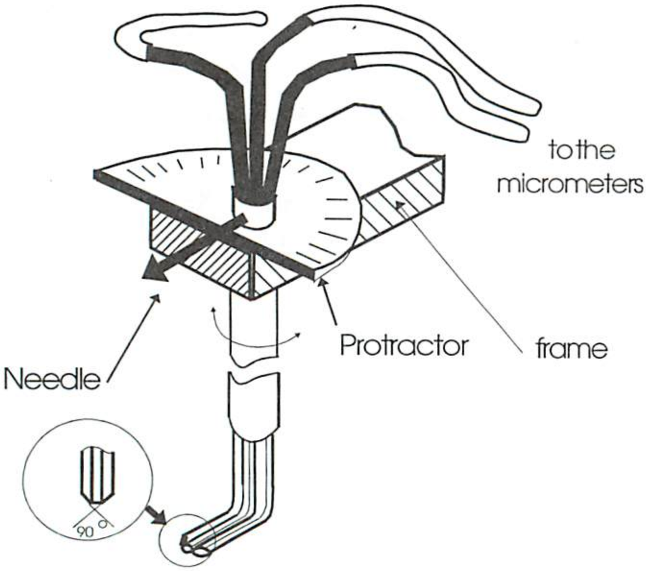

Fig. 4. The three-tube-pitot instrument.

The three-tube-pitot instrument was used to obtain the total outlet flow at the outlet surface. Three repeated measurements of the angle and velocity perpendicular to the air flow surface (Eq. 1) were performed using a grid with 16 subsections to measure the air contraction. The three-tube-pitot instrument was held at 10 mm from the duct wall to measure air flow properties at the vena contracta (Esmay and Dixon 1986). The individual outlet flow measurements were also summed up to give an equivalent air flow inside the perforated duct, starting from the end farthest away from the fan:

$$Q_{13} = V_{13}A = 0$$

$$Q_{12} = V_{12}A = V_{13}A + [((2A_o/n)) \sum_{i=1}^{n} V_{oi} \sin(\alpha_i)]_{12}{}^{**}$$

$$Q_{11} = V_{11}A = V_{12}A + [((2A_o/n)) \sum_{i=1}^{n} V_{oi} \sin(\alpha_i)]_{11}{}^{**}$$

$$Q_1 = V_1A = V_2A + [((2A_o/n))/A \sum_{i=1}^{n} V_{oi} \sin(\alpha_i)]_1{}^{**} \quad (3)$$

** 12th, 11th,....and 1st pairs of outlets

where:

V_{13} = perforated duct air velocity downstream from the 12^{th} pair of outlets (m/s), and

V_{12} = perforated duct air velocity upstream from the 12^{th} pair of outlets (m/s).

Accordingly, the air flow across the internal section of the perforated duct was compared to that summed from the flow measured outside the duct at the outlet.

RESULTS AND DISCUSSION

Measurement of static air pressure

For the static tube readings taken at different depths inside the perforated ducts, Duncan's Multiple Range Test (Table III) showed differences only for the first five locations away from the fan end (95% confidence level). Air swirling explains this observed variation in static air pressure over depth, for a distance from the fan end of 3.66 m or 9 times the

Table III: Duncan's Multiple Range Test for static tube measurements.

	Measurement point number from the fan end											
	1	2	3	4	5	6	7	8	9	10	11	12
	Measurement distance from the closed duct end (m)											
	8.5	8.0	6.8	6.1	5.5	4.3	3.7	3.1	1.9	1.3	0.6	0.1
Distance* (mm)	Duncan's analysis											
50	B	A	C	BC	BC	A	A	A	A	A	A	A
100	B	AB	C	C	C	A	A	A	A	A	A	A
150	AB	B	BC	ABC	AB	A	A	A	A	A	A	A
200	A	B	A	AB	AB	A	A	A	A	A	A	A
250	B	B	A	A	A	A	A	A	A	A	A	A
290	C	B	AB	AB	A	A	A	A	A	A	A	A

* distance from the top panel of the perforated duct.
Note: means with the same letter are not significantly different; A, B and C stand for the highest, intermediate, and lowest values, respectively.

Table IV: Duncan's Multiple Range Test to compare static tube and piezometer taps readings

	Measurement point number from the fan end											
	1	2	3	4	5	6	7	8	9	10	11	12
	Measurement distance from the closed duct end (m)											
	8.5	8.0	6.8	6.1	5.5	4.3	3.7	3.1	1.9	1.3	0.6	0.1
Method	Duncan's analysis											
Piezometric tap	A	B	B	B	B	B	A	A	A	A	A	A
Centred pitot tube	A	A	A	A	A	A	A	A	A	A	A	A

Note: means with the same letter are not significantly different; A and B stand for the highest and lowest mean values, respectively.

perforated duct's hydraulic diameter. Brundrett and Vermes (1987) also observed air swirling inside perforated ducts over a similar distance. Thereafter and for the outlet flow measurement, a 4.9 m, non-perforated duct section was added to the 1.8 m tapered section just downstream from the fan.

Duncan's Multiple Range Test (95% confidence level) indicated that static air pressures measured with the static tube and the piezometric taps were significantly different for the first 4.2 m of perforated duct length downstream from the fan end (Table IV). This 0.7 to 5.2% variation in static air pressure readings (Table V) between instruments was caused by air swirling over a distance equivalent to 9 times the duct hydraulic diameters (Table III).

For experimental accuracy and to prevent air swirling, in addition to the air straightener a non perforated duct of length equal to 10 times its hydraulic diameter should be inserted between the perforated section and the fan.

Outlet air flow

The three-tube-pitot instrument proved to be very sensitive to outlet air jet discharge angle and velocity. For the smallest angles measured (35°), a 3% coefficient of variation was obtained from the three consecutive readings. Nevertheless, the grid method applied at the outlet surface, to estimate outlet air flow, proved inaccurate when compared to the air flow inside the perforated duct (Table VI). Generally, the sum of the outlet flows exceeded that measured inside the duct by 3 to 28% for aperture ratios ($\Sigma A_o/A$) of 0.5 to 2 respectively.

Further observations indicated that the outlet air jet contraction could not be accurately detected by the grid method. The air jet leaving each outlet contracts because of its longitudinal velocity component and unless its vena contracta can be accurately measured, the outlet air flow area will appear greater than it actually is. In the present case, a 2.5 mm contraction around the edge of an outlet measuring 145 mm by 25 mm created a 25% error while being too narrow to be measured by a set of three pitot tubes, each 3 mm in diameter, held at 10 mm from the perforated duct wall. Therefore, outlet air flow can be more accurately measured from the difference in air velocity over the perforated duct's inside cross section, upstream and downstream from the outlet.

Table V: Numerical comparison of piezometric tap and static tube

Outlet	Distance*	Device		Comparison**
		Taps	Static tube	
		P_m	P_{ms}	
	(m)	(Pa)	(Pa)	(%)
1	8.5	49.2	49.2	0.0
2	8.0	49.6	51.6	3.9
3	6.8	51.2	54.0	5.2
4	6.1	54.4	55.0	1.1
5	5.5	55.0	55.8	0.7
6	4.3	56.8	57.6	1.4
7	3.7	59.2	59.2	0.0
8	3.1	59.8	59.8	0.0
9	1.9	61.0	61.0	0.0
10	1.3	61.8	61.8	0.0
11	0.6	62.2	62.0	0.0
12	0.1	61.6	61.8	0.0

Note :

P_{ms}: average static pressure obtained from a static tube (Pa);

P_m: average static pressure obtained from a wall tap (Pa), for a duct aperture ratio of 0.5;

* From the closed end of the perforated duct;

** Calculated from $100 \bullet (P_m - P_{ms}) \bullet P_{ms}^{-1}$.

Table VI: Error due to air jet contraction at outlets

Aperture ratio	Measured velocity* (m/s)	Calculated velocity** (m/s)	Error (%)
0.5	4.63	4.78	3.24
1	7.22	8.54	18.28
1.5	8.08	9.96	23.27
2	8.44	10.77	27.61

* Inside the perforated duct, upstream from the perforated section;

** From the sum of the outlet air flows.

CONCLUSION

To measure static air pressure inside perforated ventilation ducts, both static tube and piezometric taps can be used as they give similar readings. Nevertheless, air swirling inside the perforated duct, close to the fan end, must be eliminated by inserting a non perforated section of length equal to 10 times the duct's hydraulic diameter, between the fan and the perforated section. The static tube is better suited to polyethylene perforated ducts because of the flexible lining while the piezometric taps are preferred for the wooden perforated ducts.

The three-tube-pitot instrument was sensitive enough to accurately measure air jet angle and velocity at the outlet surface and demonstrated that both parameters vary over the length of the perforated duct. But, the instrument was too large to measure the air jet contraction area, which lead to errors of 3 to 28% in reading outlet air flow for aperture ratios of 0.5 to 2.0, respectively. A larger error was obtained with larger outlet openings because the same number of grid subsections was used for all four outlet sizes. Therefore, accurate outlet and duct air flow are difficult to obtain from measurements at the orifice, outside the duct, even if the discharge angle is taken into consideration. Rather, outlet air flow is more easily and accurately measured using the grid method over the duct inside cross-sectional area.

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