

ARCHIMEDES NUMBER CRITERIA FOR THE CONTROL OF COLD VENTILATION AIR JETS

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Received 22 Aug. 1985, accepted 12 March 1986

Leonard, J. J. and J. B. McQuitty. 1986. Archimedes number criteria for the control of cold ventilation air jets. *Can. Agric. Eng.* 28: 117-123.

Experiments are described in which smoke and temperature sensors were used to delineate the trajectories of cold ventilation air jets from two types of inlet, each in two locations, in a full-scale experimental facility. A drop coefficient was developed to characterize the tendencies of the jets to drop and this coefficient was found to be related to an Archimedes number. The slope of this relationship depended on the type and location of the inlet. Jets with Archimedes numbers of less than 50 appear to be satisfactory for most agricultural ventilation systems, unless they issue from inlets that are located at some distance from both walls and ceiling. In the latter case an Archimedes number of 40 is appropriate.

INTRODUCTION

This paper discusses the need for control of ventilation air flows, reviews some of the relevant theory and describes a series of experiments that has been carried out in an effort to establish criteria for the control of cold (less than -10°C) inlet air jets.

No matter what flow rate is used, ventilation results in a general movement of air through the building. The velocity of air within the building is highest at the air inlet where the flow generally may be described as a turbulent jet. At the boundary of this jet there is a continuous exchange of momentum with the surrounding air, giving rise to entrainment of the surrounding air and a reduction of jet velocity. This, in turn, results in secondary air flows within the room and an airflow pattern is set up within the ventilated space. Ideally, the pattern of secondary airflows will result in complete mixing of the ventilation air. However, as has been described by Barber and Ogilvie (1982), incomplete mixing can also result. Full-scale flow visualisation studies by Randall (1975), Randall and Battams (1976) and Boon (1978) have demonstrated that, in addition to the initial velocity of the inlet air, the layout of pens and design of partition structures within the building exert a great influence on the airflow patterns within the building. These airflow patterns are of particular significance when considering airflow over the housed animals and their effects have been described by various researchers such as Bond et al. (1965), Baxter (1984) and Sällvik and Walberg (1984).

Instability of airflow patterns within a building is most likely to occur at low ventilation rates (Randall 1980) and these generally coincide with the winter air temperatures most conducive to adverse

energy losses from the housed animals due to unwanted airflows. Since the initial flow path from the air inlets must be predictable and stable before any rational design of penning and other internal structures is carried out, the designer of ventilation systems requires some means of ensuring this. In practice, this requirement has translated into the adoption of general design rules (e.g., Winchell (1982), Turnbull and Bird (1980)) aimed at providing air velocities that are sufficient to ensure adequate control and mixing of cold inlet air with warm inside air.

Despite these guidelines, inlet designs are often such that continuous control of inlets in response to changing air flows is impossible, inconvenient or ignored. In addition, under very cold conditions and particularly with old structures, great difficulty is encountered in trying to adjust inlets to control very low air flow rates. There is, therefore, a need to reassess the criteria used in the control of inlets and the design of the inlets themselves. To this end, recent studies have called for a more rational and analytical approach to the problem (Kaul et al. 1975; Randall and Battams 1979; Barber et al. 1982).

Cold Air Jets

The theory describing the behavior of both isothermal and nonisothermal air jets is well documented (e.g., American Association of Heating, Refrigeration and Air Conditioning Engineers (1981), Abramovich (1963), Baturin (1972), Walker (1977)) and will not be reviewed in detail in this paper. However, some discussion of cold nonisothermal jets is appropriate.

Whereas the axis of, in the case of a plane jet, the central plane, of an isothermal jet discharging horizontally into a stagnant environment will be straight, the axis of a nonisothermal jet will be curved

due to the effect of buoyancy or gravity. The axis of a warm jet will curve upwards and that of a cold jet will curve downwards. The curve described by the axis is called the jet trajectory and is of importance in ventilation design as well as in other fields such as submarine disposal of effluent and the dispersal of smoke plumes.

The influence of buoyancy on the jet has led to the use of a dimensionless ratio of buoyancy to momentum forces in order to characterize and predict jet trajectories. Depending on the precise application and definition of the terms involved, this ratio is referred to variously as a buoyancy number, a densimetric Froude number, a Richardson's number or an Archimedes number. For the purposes of this paper the term Archimedes number will be used.

In order to predict the paths of ventilating air jets in animal housing, Randall and Battams (1979) proposed the use of an Archimedes number based on work by Mullejans (1966) and Jackman (1970). This "corrected Archimedes number", Ar , was defined as:

$$Ar = \frac{g(T_s - T_0) C b h (B + H) B H}{(T_s + T_0) Q^2} \quad (1)$$

Where g = acceleration due to gravity (m/s^2), T_s = temperature of heated surface (K), T_0 = temperature of inlet air (K), C = orifice discharge coefficient, b = width of inlet slot (m), h = height of inlet slot (m), B = width of room (m), H = height of room (m) and Q = flow rate (m^3/s).

Embodying, as it does, the ratio of forces acting on the jet, the Archimedes number would appear to offer a useful criterion for design and control of ventilation inlets. Indeed, in the experiments of Randall and Battams (1979), jets with $Ar < 30$ were observed to remain horizon-

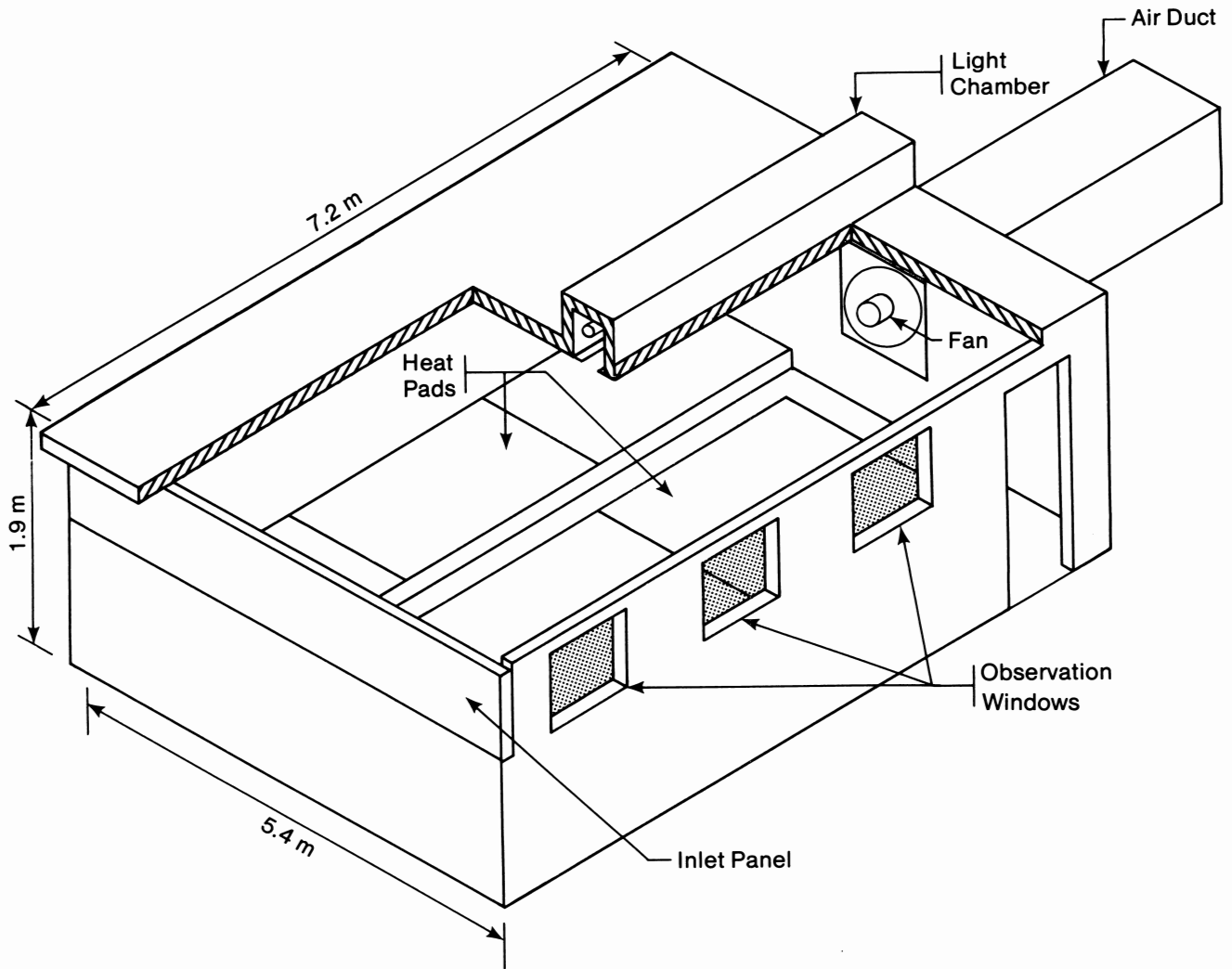


Figure 1. Schematic diagram of experimental facility.

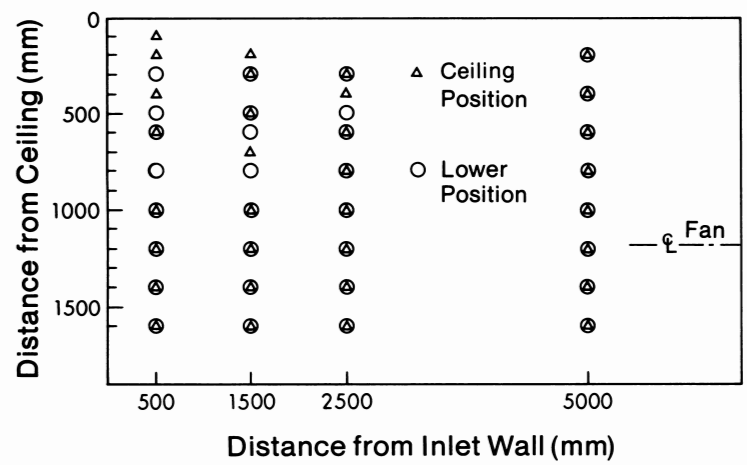


Figure 2. Location of temperature sensors in air space for top and lower inlet positions.

tal while those with $Ar > 71$ fell on entry to the ventilated room. However, these experiments were carried out with a minimum jet temperature of 0°C and were concerned only with slot inlets located at the ceiling and extending the full width of the room. This paper describes experi-

ments that have been carried out to provide data on the relationship between Ar and the trajectories of low temperature air jets ($< -10^{\circ}\text{C}$). The slot inlets used were of two different widths and were located at different vertical locations in the inlet wall.

EXPERIMENTAL FACILITY

The Ventilated Room

The facility used for these experiments has been described in detail elsewhere (Leonard and McQuitty 1984) and is illustrated in Fig. 1. The ventilated room consisted of a room having internal dimensions of $7.2 \times 5.4 \times 1.9$ m. These dimensions were chosen principally on the basis of available space but, according to Linke (1966) and Kaul et al. (1975), should have been sufficient to allow unimpeded penetration of the inlet jet. The work of these authors indicated that, regardless of jet location in the inlet wall, there exists a maximum jet length of about three room heights. Part of the inlet wall was removeable so that different inlet configurations could be tested, observation windows were located along one side of the chamber and a vertical beam of light was obtained from fluorescent tubes in a light chamber that ran along the length of the room above the ceiling. Outside air was drawn through the room by means of a variable speed fan which dis-

TABLE I. INSTRUMENTATION SENSORS

Channel	Sensors
1	Wind direction
2	Wind speed
3	Fan speed
4	Pressure difference
5	Thermistor voltage
6-11	Heat pad temperatures
12-19	Air temperatures (Group 1)
20-27	Air temperatures (Group 2)
28-35	Air temperatures (Group 3)
36-43	Air temperatures (Group 4)
44,45	Inlet air temperatures
46	Outside air temperature
47	Outlet temperature (fan duct)
48	Wet-bulb temperature

TABLE II. SUMMARY OF TESTS

Date	Code	Temp. (°C)	Wind (m/s)
23 Dec. 1984	FT1	-26	2
26 Dec. 1984	FT2	-22	1
09 Jan. 1985	FT3	-15	1
09 Jan. 1985	FL1	-13	1
30 Jan. 1985	FL2	-26	1
01 Feb. 1985	HT1	-21	1
03 Feb. 1985	HT2	-20	2
06 Feb. 1985	HT3	-16	1
03 Mar. 1985	HL1	-8	0
04 Mar. 1985	HL2	-10	3

two inlet types each in two positions. The inlets were tested in locations adjacent to the ceiling and approximately 300 mm below the ceiling of the room. For convenience, these configurations were identified according to the following code:

FT = full width, ceiling position
 FL = full width, lower position
 HT = half width, ceiling position
 HL = half width, lower position

charged into a duct that was used for flow measurement.

Two inlets were tested. The first of these was a slot inlet extending across the full width of the room and approximately 25 mm in height. The second was a slot half the width of the first, located in the middle of the inlet wall and of the same effective area as the first. Both inlets could be located at various heights in the inlet wall.

The presence of animals in the room was simulated using six water-filled heating pads. Each pad was equipped with electric heaters rated at 720 W and thermostat controls set at approximately 30°C. The heat output, set temperature and area covered by the pads approximately corresponded to occupation of the room by 48 pigs averaging 54 kg live-weight (Turnbull and Bird 1980).

Instrumentation

The facility was instrumented using a Rockwell AIM65 microcomputer interfaced with three Rockwell RM65/5302E analog-to-digital conversion boards giving a total capacity of 48 channels of input data. The utilisation of these channels is detailed in Table I. Data were recorded on magnetic tape and were then transferred to floppy disk for subsequent processing on a computer.

All temperatures were measured using thermistors, 32 of which were used to delineate the path of the cold inlet jet. These sensors were arranged in four vertical lines of eight along the major axis of the room. The location of these groups is illustrated in Fig. 2 together with the vertical spacing within groups which varied depending on the inlet configuration being tested. The thermistors used (UUB31J1, Fenwal Electronics Inc., Framingham, Mass.) were matched-curve sensors with a rated accuracy of $\pm 0.25^\circ\text{C}$ over the range used. They were connected in voltage divider circuits with a common supply voltage.

To supplement the data on jet tra-

jectories obtained from the temperature sensors, smoke was injected into the inlet at the location of the vertical light beam and photographs of the smoke path were taken from the observation windows. The smoke used was titanium oxide which was obtained by bubbling moist air through titanium tetrachloride. Both temperature and smoke concentration profiles would be wider than the velocity profile of a jet, but are considered quite adequate for indicating the trajectory since their centerlines would be coincident with that of the velocity profile.

Prior to testing with low-temperature air, air flow through the room was calibrated against fan speed and differential pressure for each inlet configuration. Flow rates were measured in the fan duct using both a hot-thermistor anemometer and sulphur hexafluoride tracer gas (Leonard et al. 1984). All calibrations were corrected for temperature.

EXPERIMENTAL PROCEDURE

Constraints

The nature and scope of the experimental procedures followed in this project were governed by a number of constraints. The most significant of these was the requirement for low air temperatures. For the purposes of this work, low air temperature was defined as being below -10°C and, in general, data were gathered only when the outside air temperature was below this value. Exceptions to this occurred at the end of the winter in order to complete the experiment. In these cases, the air temperature was approximately -8°C .

Another climate-related constraint was the need for low wind velocities. At low fan speeds, wind velocities in excess of 4 m/s tended to cause pressure differences between inside and outside the room that dominated the effect of the fan.

Since the experimental work was to be completed in one winter, the above constraints limited the number of days which would be available for data collection which, in turn, governed the number of inlet configurations that could be tested. A decision was made to investigate the

Experimental Design

Since the number of replications of a given test would be limited by the constraints detailed above, and owing to the difficulty of quantifying jet characteristics such as trajectory, a rigorous statistical experimental design was considered to be impractical. Instead, the general aim of the experimental design was to maximize the data that could be obtained within the time available in order to verify the experimental results of previous researchers who had used warmer inlet air.

Thus, for a given inlet configuration, the experimental requirement was for a number of tests that would allow the observation of the jet trajectory for different values of Ar. Since there was no control over inlet temperature, and since geometric variables were constant for a given inlet, this was achieved by varying the airflow rate (i.e., the fan speed). Data were obtained by carrying out a series of tests at different fan speeds with a minimum of two series being carried out on each inlet configuration. To prevent confounding of results with time- or weather-dependent variables, no two series were carried out on the same inlet configuration in the same day.

Although complete randomization of the order in which the test series were carried out would have been desirable, this was hampered by the physical difficulty of changing inlets and sealing them in cold weather. Consequently, all tests on a given configuration were done in sequence before the configuration was changed. Table II summarizes the tests carried out and shows the order of testing together with relevant prevailing weather conditions. A test series is identified by the inlet configuration code followed by the series number.

Procedure

The general format of a series of test runs was to uncover all the heat pads and to open the inlet and fan duct outlet before setting the fan to run at a slow speed. The data recording system was started and was set to scan all sensors every 2 min. At least 12 min were allowed to elapse so that

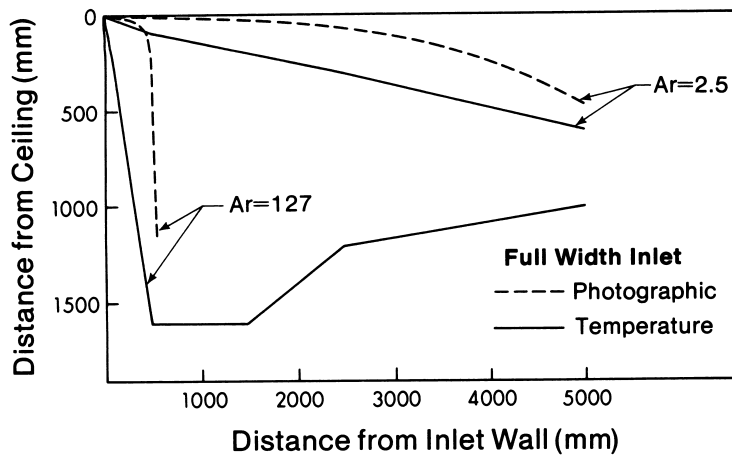


Figure 3. Sample jet trajectories for full-width inlet, top position.

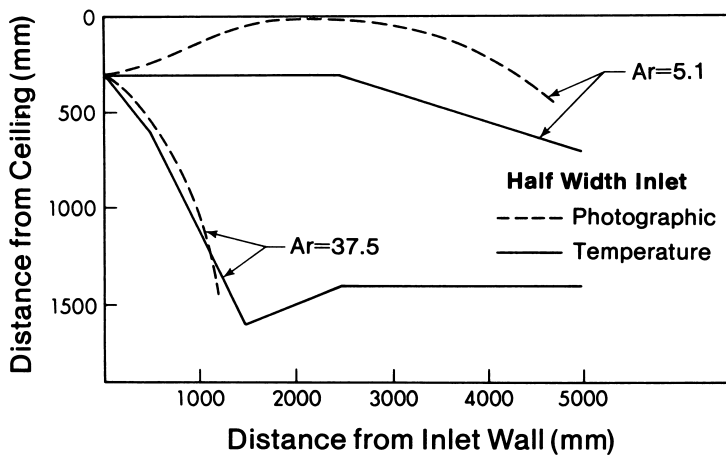


Figure 4. Sample jet trajectories for half-width inlet, lower position.

the room could equilibrate. At the end of this period, the smoke generator was started and the inlet jet was photographed at a time approximately coincident with a data scan to enable subsequent correlation of photographic and temperature data. The time at which photographs were taken was noted and, as a further check, sketches were made of the apparent jet trajectories using the thermistor strings as reference points.

Data were recorded throughout the test and were later checked against manual readings of temperatures, fan speed and pressure differential. The zero of the differential pressure indicator was checked prior to each run. In addition, an approximate check on airflow rate was carried out using the hot-thermistor anemometer.

RESULTS

The data that were of interest in determining the jet trajectories were the temperatures indicated by the array of thermistors in the ventilated room. To reduce these to a similar basis, they were expressed as dimensionless temperature dif-

ferences according to the following equation:

$$\Delta T_n = (T_n - T_0)/(T_d - T_0) \quad (2)$$

where ΔT_n = dimensionless temperature difference at location n , T_n = temperature at location n (K), T_0 = temperature at the inlet (K), and T_d = temperature downstream of the fan (K).

For each vertical group of thermistors, the minimum temperature difference was identified and taken to indicate the sensor closest to the jet centerline. Where two sensors in a string indicated the same temperature difference, the centerline of the jet was assumed to pass midway between the sensors. Having identified the location of the jet centerline at each vertical string of sensors, an approximate plot of the total jet trajectory could be obtained. Examples of such plots are shown in Figs. 3 and 4. The temperature-based plots shown in these figures should not be interpreted as portraying the actual jet trajectories since the sensors, particularly those in the upper part of the room, may not have been located near the actual jet centerline. Sim-

ilarly, the sharp changes in direction portrayed in these plots are due to, and coincide with, the location of the temperature sensors. Nevertheless, the plots do indicate whether a jet fell on entry or remained in the upper part of the airspace. This was confirmed by the photographic record and sketches of the photographically derived trajectories which are shown for comparison.

For each "trajectory" plot, an Archimedes number was calculated using Eq. 1. The temperature of the heated surface, T_s , was calculated as the mean of the surface temperatures of the six heat pads. The orifice coefficient, C , was taken to have a value of 0.6 for all inlets. This value is the same as that used by Jackman (1970) and Randall and Battams (1979). Since, in some instances, the calibration of flow rate against pressure differential may have been affected by wind at low fan speeds, the flow rates used in the calculation of Ar were based on the fan speed calibration.

Although Randall and Battams (1979) reported that jets having values of Ar between 30 and 71 exhibited inconsistent behavior, sometimes falling on entry and sometimes remaining horizontal, such behavior was not observed in these tests. Rather, the jet trajectories seemed to display a general and continuous tendency to remain horizontal as Ar was decreased. These continuous "families" of trajectories are analogous to those obtained by Fan and Brooks (1969) in their numerical solution of the trajectories of warm, submarine effluent plumes.

Having, thus, a continuum of trajectories, the classification used by Randall and Battams (1979) (dropping, horizontal or unstable) was deemed to be inadequate, especially in the assessment of the effects of inlet width and position. Therefore, a more precise descriptive measure was sought. A general equation describing jet trajectories would provide such a measure. On the basis of work concerned with free jets (Frean and Billington 1955; Koestel 1955), this equation could be expected to be of the general form:

$$Y = Ar \cdot f(X) \quad (3)$$

where Y = dimensionless vertical distance, and X = dimensionless horizontal distance.

Sufficient data were not available from this study to determine the precise form of $f(X)$ in Eq. 3. However, a single number describing the tendency of the jet to drop would also be useful in establishing design criteria and in the comparison of inlet performance. Ideally, this number would

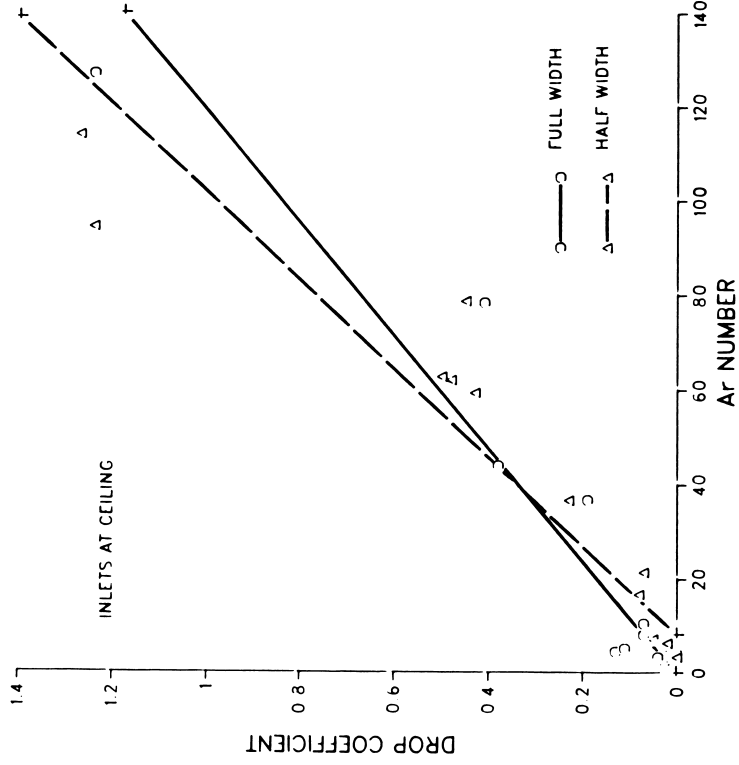


Figure 5. Plot of drop coefficient against Archimedes number for top inlet position.

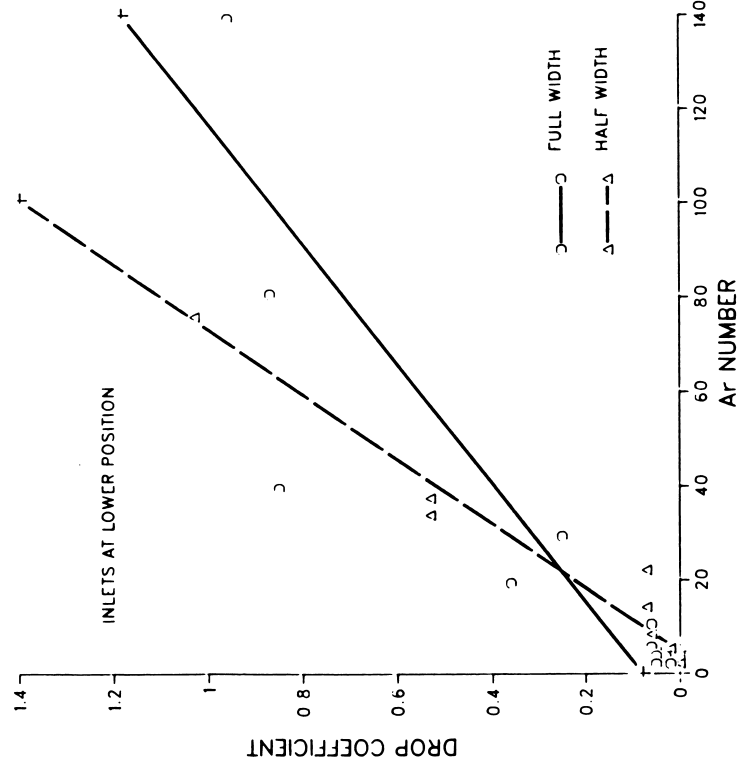


Figure 6. Plot of drop coefficient against Archimedes number for lower inlet position.

be dimensionless and applicable to any type of room/inlet geometry. In order to provide such a number, the concept of a drop coefficient is postulated.

If the location of the jet centerline can be defined at n points in the room, each having coordinates relative to the jet ori-

face of (x, y) , then the drop coefficient, Z , may be defined as:

$$Z = \sum(y_i/x_i)/n \quad (4)$$

Equation 4 indicates that Z may be thought of as an average slope of the jet trajectory and that the larger the value of

Z , the more rapidly the jet drops after entry into the ventilated space. Z is more sensitive to the initial part of the trajectory because division by the horizontal distances from the orifice (x_i) effectively gives more weight to the early part of the jet. In this region, temperature differences were greatest and dissipation was minimal, allowing the best possible delineation of the trajectory.

Using Eq. 4, values of Z were calculated for each test. Because of the uncertainty of the true location of the jet centerline in the upper part of the airspace, an approximation was made whereby, if the minimum dimensionless temperature difference was indicated by the top sensor in a group, then the drop of the jet (i.e., y) was said to be 0 at that horizontal distance from the inlet (i.e., x).

To facilitate comparison of different inlets, the values of Z were plotted, for each inlet configuration, against Ar . Examination of general equations for the trajectories of both heated and chilled free jets (Frean and Billington 1955; Koestel 1955) indicates that, for these jets, Z would be related linearly to Ar . Assuming that Eq. 3 is applicable, the same could be expected for the jets of this study and the plots of the data, together with the best-fit straight lines obtained by least squares linear regression, are shown in Figs. 5 and 6. The equations to these curves are shown in Table III, together with the equation fitted to all the data regardless of inlet type or position. The values of R^2 for these regressions vary from 0.78 to 0.95 and, although higher values of R^2 were obtained for quadratic and cubic functions, there seems to be little justification for using these, instead of linear functions, as the basis for comparing inlet performance. Further, the error implied by the R^2 values does not appear to be unreasonable.

With low velocity jets, measurements of both Ar and Z were subject to greater error than with high velocity jets. As can be seen from Figs. 3 and 4, "trajectories" of jets with high values of Ar appear to rise after falling initially. In fact, the plotting of trajectories of these low energy jets so far into the airspace may be misleading since they dissipate quite rapidly. Although the smoke tracer injected with these jets was observed to rise due to convection off the warm pad surfaces, the true location of the jet centerline beyond the second line of sensors cannot be fixed with certainty. This uncertainty would have resulted in some error in the calculation of Z although, because of the dominant effect of the early part of the jet, the

TABLE III. REGRESSION EQUATIONS FOR Z AGAINST Ar

Inlet configuration	Equation	R^2	Data pairs
FT	$Z = 0.0084Ar - 0.0013$	0.90	10
FL	$Z = 0.0079Ar + 0.0782$	0.78	12
HT	$Z = 0.0107Ar - 0.0878$	0.89	15
HL	$Z = 0.0146Ar - 0.0692$	0.95	11
All data	$Z = 0.0094Ar - 0.0015$	0.83	48

TABLE IV. MAXIMUM Ar FOR $Z < 0.25$ AND $Z < 0.5$

Inlet configuration	$Z < 0.25$	$Z < 0.5$
FT	30	60
FL	22	53
HT	32	55
HL	22	39
All data	27	53

error would be small.

More significant errors would probably be due to uncertainties associated with flow measurement. These were due to the fact that the calibration of both fan speed and pressure differential against flow rate were inherently less accurate at low flows. A further consideration is that any effects of wind would have been of greatest significance at low flow rates. Taken together, these factors could reasonably account for the unexplained error of the regression analyses.

DISCUSSION

General Jet Behavior

From the temperature data, the photographic record and observations recorded during the tests, a number of general comments can be made on the behavior of the cold jets studied. These concern the penetration of the jets into the room and the attachment of jets to the ceiling.

The work of Linke (1966) and Kaul et al. (1975) mentioned above suggests that, in these experiments, no jet should have penetrated further than 5.7 m into the room (three times the ceiling height). In fact, high speed jets, or those with low values of Ar , were identified readily by temperature at a distance of 5 m into the room, and in some instances the jet was identifiable with the smoke tracer, albeit in a dispersed form, for the full length of the room (7.2 m). Since the penetration, or throw, of jets has implications in the location of inlets and the maximum width of buildings, further investigations should be carried out to check the penetration distances that can be expected from ventilation jets.

With the exception of the slowest jets (high Ar), all jets tended to adhere to the ceiling of the room. This, of course, counteracted the tendency of the jets to drop and was to be expected for the jets discharging adjacent to the ceiling. However, the attraction to the ceiling of the lower jets was not so predictable.

Baturin (1972) has reported experiments indicating that cold jets would cling to a ceiling if the jet orifice was within four orifice widths of the ceiling. In the present experiments, using the lower inlet location, the orifices were approximately

6 and 12 orifice widths from the ceiling for the half- and full-width slots, respectively. An additional experiment was carried out with the full-width slot located approximately 24 orifice widths below the ceiling and, at this location, the jet would not attach to the ceiling at any velocity. Because attachment to the ceiling counteracts the dropping of the jet, and because of the relevance of this effect to inlet design and location, more work is required to determine the limiting distance of the orifice below the ceiling beyond which jets will not attach.

Comparison of Inlet Configurations

The graphs shown in Figs. 5 and 6, together with the equations shown in Table III, illustrate the usefulness of the drop coefficient, Z , to describe the severity of jet drop. In general, the greater the slope of the regression line, the greater the tendency of the jet to drop. Thus, it is of interest to note that the slopes of the regression lines appear to depend on the inlet type and location.

Examination of the equations in Table III indicates that the tendency of full-width jets to drop was not affected by the location of the jet and was less than that of the half-width jets. In contrast, the half-width jet from the lower inlet location showed a greater tendency to drop than that from the ceiling location. These results can be explained qualitatively in terms of air entrainment and the Coanda effect.

In the case of a full-width jet discharging along the ceiling, entrainment of room air can occur only on the underside of the jet. The tendency to entrain air from the boundary layer adjacent to the ceiling "pulls" the jet towards the ceiling while the walls limit entrainment at the sides of the jet. Except for a small portion of the jet close to the orifice, the situation is identical for a full-width jet discharging at a small distance from the ceiling. Nevertheless, the slope of the regression line for the full-width jet in the lower position could be expected to be, if anything, greater than that for the upper position. The fact that the results do not indicate this is not considered to be significant bearing in mind the closeness of the slopes

and the lower regression coefficient of the equation for the lower position inlet.

In contrast to full-width jets, half-width jets are able to entrain air along their sides and, in addition, the area of limited entrainment at the ceiling is smaller. The net result is a reduction in the attraction of the jet to the ceiling. As a half-width jet is moved away from the ceiling, entrainment at the top of the jet increases until, at some distance from the ceiling, entrainment occurs all around the jet and it remains unattached along its entire length. The smaller the degree of attachment to the ceiling, the greater the effect of the buoyancy forces tending to make the jet drop.

Archimedes Number Criteria for Jets

Examination of all the temperature-derived trajectory plots indicated that all jets with a drop coefficient, Z , greater than 0.5 fell to the floor within 0.5 m of entry. Also, all those jets with Z greater than 0.25 fell at least 1 m within 1.5 m of entry. Thus, depending on what value of Z is considered acceptable, design values of Ar may be determined from the regression equations of Table III. Some sample values are tabulated in Table IV for each inlet configuration and for the two values of Z mentioned above.

Thus, if a design required that Z be kept less than 0.25, then the maximum allowable values of Ar would be similar for the two inlets at the ceiling and for the two removed from the ceiling. The values reflect the tendencies of jets from the two locations to drop and the value of $Ar = 30$, proposed by Randall and Battams (1979), would be applicable to ceiling inlets while that of $Ar = 20$ would be more appropriate for the lower inlets.

However, the requirement that Z be less than 0.25 is, perhaps, too stringent for many ventilation systems, where it is sufficient simply to prevent jets dropping to the floor on entry. In these cases, the less stringent requirement of $Z < 0.5$ could be quite acceptable and would allow considerably higher values of Ar . For instance, on the basis of the results of these experiments, Ar values of 50 could be tolerated for all inlets, except those removed from both ceiling and walls, where a maximum value of 40 would be appropriate.

CONCLUSIONS

(1) The use of a drop coefficient, Z , appears to be useful in describing trajectories of cold jets.

(2) Evidence existed of a linear relationship between Archimedes number, Ar , and drop coefficient, Z , with the slope being dependent on the inlet configuration.

(3) On the basis that jet trajectories with $Z < 0.5$ would be satisfactory for most animal housing applications, jets from full-width continuous slots or from inlets adjacent to the ceiling should have Ar values of less than 50. For other inlets, Ar should be less than 40.

ACKNOWLEDGMENTS

We wish to acknowledge the assistance of Mr. R. Larson, Department of Agricultural Engineering, University of Alberta, in the construction and calibration of the experimental facility. Construction of the facility was funded by the Alberta Agricultural Research Council under the Farming for the Future Program of the Alberta Heritage Fund and by the Natural Sciences and Engineering Research Council of Canada.

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