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A STUDY ON THE CHARACTERISTICS OF AIRFLOW IN A FULL SCALE ROOM WITH A SLOT WALL INLET BENEATH THE CEILING

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ABSTRACT

Symmetry is not a sufficient condition for the design of a ventilated room to generate two-dimensional airflow. Three-dimensional effects were observed in a symmetrically designed 3m × 5m × 8.5m test room having a 0.019m slot inlet opening height under the ceiling in the one end wall. The ceiling jet velocity profile measured in the symmetric plane agreed well with the jet models for two-dimensional flow, but large differences were found out of the symmetric plane. The velocities in the jet 4.5m downstream from the inlet wall were up to a factor of two higher on the one side than the other side. During the measurement period the side with high velocities occasionally changed without any obvious disturbance in the room. Two semi-stable statuses were observed. The measured velocities in the symmetric centre plane were only slightly effected by the switch-over and remained at the same level throughout the experiment. In both statuses the return air direction diverged 30° from the symmetric plane. Systematic validation of flow behaviour is thus necessary before the assumption of two-dimensional flow should be accepted and a study is carried out in the symmetric plane only.

KEYWORDS

Airflow Characteristics; Full-scale experiments; Slot-inlet ventilation; Attached jets

INTRODUCTION

To validate Computational Fluid Dynamics (CFD) simulations of indoor air the measured data using well-defined ventilated enclosures are recommended. The enclosures can be scale models (Nielsen, 1974; Timmons et al., 1986), or full-scale rooms (Hoff, 1995). A commonly used design is a rectangular room with a slot inlet beneath the ceiling and a slot outlet near the floor (Timmons et al., 1986; Hoff, 1995). In such room two-dimensional (2D) airflow patterns are assumed, and measurements are taken in the symmetric plane only. Few systematic experimental data are available, however, throughout well defined, full-scale rooms to check the CFD code and to analyse the boundary conditions.

An intensive joint project that the authors are involved is focusing on the application of CFD in the analysis of air motion and velocity characteristics in livestock buildings. One of inessential intentions was to validate algorithms for the simple situation of 2D flows in an empty room as a reference, and then to provide the necessary information on boundary conditions for animal housing. The hypothesis was that the use of a geometrically symmetric room was sufficient to achieve 2D airflows. In this paper results of the measurements in the empty room are presented.

MATERIAL AND METHODS

The length (L) of the experimental room was 8.5m, the height (H) 3m, and the width (W) 5m in order to represent a common piglet producing section. A slot opening with a length (w) of 5m was placed just below the ceiling. The height of the inlet slot was 0.1m at fully open. The actual opening height could be adjusted in the range form 0 to 0.1 m with a 0.24m×5m bottom-hinged flap. To simulate cool weather conditions an inlet height (h) of 0.019m was chosen.

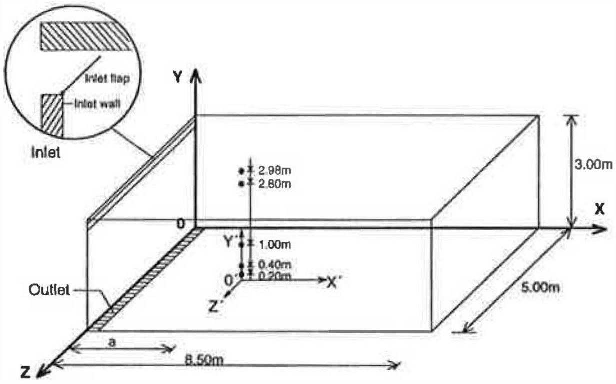

Figure 1. Room geometry and positions of inlet, outlet and sensors. a = 2.68m, 3.5m and 4.5 m.

Comparing the recommend geometry for creating 2D flows by Nielsen (1990), which was 9m (L) × 3m (H) × 3m (W) with a full width slot inlet of 0.168m (h_{max}), the differences were: (1) The W/H ratio was extended from 1 to 1.66. (2) The L/H ratio was reduced from 3 to 2.83. (3) The h/H ratio became 0.006, nearly a factor 10 smaller than Nielsen (1990) suggested.

The floor of the experimental room was raised 0.6 m above the building floor so it was possible to create a 4.8 m by 0.13 m 20% open slatted floor with exhaust to a below-floor channel along the inlet wall, figure 1. The airflow rate was measured at exhaust with an orifice system (ISO 5167-1) with estimated uncertainty of ±3%. The room was as airtight. Leakage test was performed and the leakage data was considered in the computing of inlet airflow rate.

JET MODELS

The air jet through a slot beneath the ceiling is generally referred to as an attached plan jet. The inlet the maximum velocity u_x in the jet downstream can be estimated by (Grimitlin,1970; ASHRAE, 1997)

$$\frac{u_x}{u_o} = C_p \left(\frac{h_o}{x + x_o} \right)^{1/2} \qquad (1)$$

where u_o is the inlet velocity, C_p is the velocity decay constant for a slot inlet, h_o is the effective opening height of the inlet, x is the distance downstream from the inlet and x_o is the distance from the inlet opening to the virtual origin of the jet. For a narrow slot inlet opening without deflects x_o can be ignored. For a jet generated by a slot inlet beneath the ceiling with bottom hinged flap, C_p is approximately 3.8 (Förthmann, 1934; Nielsen, 1997). The effective opening height h_o can be estimated as the discharge coefficient, C_d, multiplied with the geometric height, h.

In the similarity region, the velocity profiles remain identical in dimensionless form. The universal velocity profile for an attached plan jet could be stated as (Verhoff, 1963):

$$\frac{u}{u_x} = 1.481 \left[\frac{y}{\delta(x + x_o)} \right]^{\frac{1}{7}} \left(1 - erf(0.68 \frac{y}{\delta(x + x_o)}) \right) \qquad (2)$$

where y is the vertical distance from the ceiling to the point, δ is the expansion coefficient for the jet, and *erf* is an error function. According to flow similarity in the jet δ is considered to be a constant. It defines the slope of the line where the velocity is half of the maximum velocity. This line is often used to characterise the expansion of the jet. The product $\delta(x+x_0)$ thus expresses the vertical distance from the ceiling to the point where the velocity is half of the maximum velocity. Equation 2 includes descriptions of the boundary layer near the ceiling where the velocity increases from zero to maximum.

Another simpler way to describe an attached plan jet could be found in Becher (1972) and ASHRAE (1997), where the velocity profile is proposed as half of a free plane jet:

$$\frac{u}{u_x} = 10^{-0.3030 \left[\frac{y}{\delta(x+x_o)} \right]^2} \qquad (3)$$

where the boundary layer near the ceiling is omitted, but the rest of the profile is similar to equation 2. In ventilated room spaces a value of δ in the range from 0.06 to 0.14 is suggested, mainly depending of room geometry, inlet design and the Reynolds number (Nielsen & Möller, 1988).

MEASUREMENTS

The inlet velocity was adjusted to 4.8 m/s in the experiments. That gave a Reynolds number of 5100 with the inlet opening h=0.019m. Velocity measurements were carried out with a multi-channel thermistor based system (Zhang & Morsing 1994). The pre-calibration in the range from 0.1 to 6 m/s provides the uncertainties within ±5% for 0.1-1 m/s and ±3% for velocity above 1 m/s.

The measurements were conducted in total 29 measurement positions in a vertical line (y-direction) on a fixture (exchangeable in two level) with the top two positions of 0.02m and 0.1m from the ceiling and 0.1m apart from each other down to the floor for the rest. The fixture was placed downstream at 2.68, 3.5, and 4.5 m from the inlet wall (x-direction) and in the planes z = 0.5, 1.5, 2.5 (symmetric plane), 3.5, and 4.5 m, resulting in 29×3×5 sensor positions in the room (figure 1). The measurement time was 30 minutes with scan rate 10 Hz and averaging every 5 minutes.

RESULTS

Prescribed velocity

In figure 2(*a*) the velocity profiles are shown in the symmetric plane at the three downstream positions. The dimensionless velocity u/u_x is presented as a function of the non-dimensional distance from the ceiling y/x. The velocity u_x is estimated according to equation 1. Smoke tests showed that the non-dimensional total width of the jet was in the order of 0.2. The data up to that width was thus extracted and used for non-linear parameter estimation on the basis of equation 2. The estimated expansion coefficient, δ, was 0.093 m/m ± 0.0053 ($P<0.05$). In figure 2(*a*) the estimated profile of the jet, using equation 2, is shown as a solid line. It is seen that the estimated profile fits well to the measured data. Using the estimated δ in equation 3 gives the dotted line in figure 2(*a*), and the deviation near the ceiling is clearly seen.

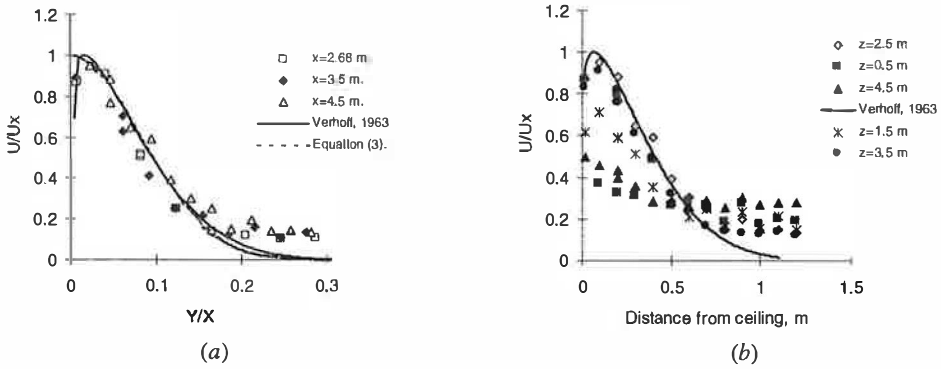

Figure 2. (*a*) Velocity profiles of the ceiling jet in the symmetric plane z = 2.5 m. (b) Velocity profiles of the jet in five z-planes at the distance x = 4.5 m from the inlet wall.

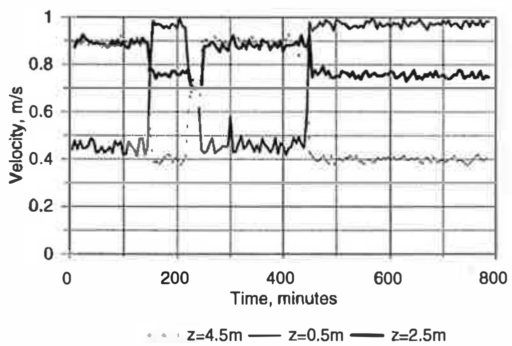

Figure 3. Velocities measured in the ceiling jet at the positions of x=4.5m; z = 0.5, 2.5, and 4.5m; and y = 2.98 m (0.2m from ceiling) showing the semi-stable airflow statuses in the room.

Two dimensional airflow

To check the two-dimensionality of the airflow in the room the data at x = 4.5 m are used. The air velocity profiles for z = 0.5, 1.5, 2.5, 3.5 and 4.5m are shown in figure 2(*b*). It is seen that the velocity profiles on both sides of the symmetric plane were different from the velocities measured in the symmetric plane. In general the average velocities out of the symmetric plane were lower. The velocities measured outside the symmetric plane were not in accordance with the 2D flow expectation, which assumes similar velocity profiles in all planes parallel to the symmetric plane.

To evaluate the findings, additional measurements were carried out. Six velocity sensors were placed 0.02 m and 0.2 m below the ceiling at positions z = 0.5, 2.5 and 4.5 m from the wall. Continuous measurements were performed for 8 hours in a scan rate of 5 scans/sec saving averages every 5 minutes. The results from the sensors placed 0.2 m below the ceiling are shown in figure 3. It can be seen that the velocities at one side of the symmetric plane were a factor of up to two higher than the other side. During the measurement period the side with high velocities occasionally changed without any obvious disturbance in the room. Smoke tests showed that the jet for some periods turned towards the right downstream corner, and then changed and turned to the left, showing two semi-stable statuses. The measured velocities in the symmetric centre plane were only slightly effected by the switch-over and remained at the same level throughout the experiment.

To study the impact on the return airflow pattern near the floor. a low velocity direction sensor was constructed. The sensor was placed at floor level in the centre plane (x, y, z = 6.5m, 0.2m, 2,5m). In both semi-stable conditions the return air direction diverged 30° from the symmetric plane.

DISCUSSIONS

It is surprising that the 3-D flows encountered in this study are not explicitly reported in many previous studies. Compared with the recommendation given by Nielsen (1990), the differences between the two test rooms were the ratio of inlet opening height to room height, *h/H*, and the ratio of room width to room height, W/H, may be the main reasons.

The ratio of inlet opening to room height used in this study was about a factor of 10 smaller than the one used by Nielsen (1990). The smaller ratio could be an important explanation for the 3-D flow. The inlet opening height and inlet air velocity chosen in this study, however, were to represent practical conditions of a weaning pig room. Increasing inlet opening height or initial air velocity may reduce the 3-D effects, but this would result in a too high ventilation rate and a too high air velocity in the occupied zone – and that would not be representative for winter ventilation of livestock buildings. Systematic validation of flow behaviour is thus necessary before the assumption of 2D flow is accepted and the measurements are carried out in the symmetric plane only.

3D CFD simulations with wall function as described by Bjerg et al. (1999) indicate that the horizontal velocity profile of a ceiling jet in a very wide room space (W/H = 18) contains a periodical variation with an interval of 3H. In the room with W/H = 1.67 the velocity profile in a horizontal plane contains a part of the periodical curve. The validation of the CFD simulation has not been performed in experiments with room width ratio larger than 1.67. In a test room with room width ratio equal to 1 and room length equal to 3H no significant 3-D effects were found, however, whether in measurements (Nielsen et al 1978) nor in CFD-calculations (Bjerg et al 1999).

CONCLUSIONS

Symmetric room geometry is not a sufficient condition for the design of a ventilated room where 2D airflow is to be generated. The velocities at one side of the symmetric plane were a factor of up to two higher than at the other side. During the measurement period the side with high velocities occasionally changed without any obvious disturbance in the room. Semi-stable flow behaviour was observed. The measured velocities in the symmetric centre plane were only slightly effected by the switch-over ai remained at the same level throughout the experiment. In both conditions the return air directi diverged 30° from the symmetric plane.

The ratios of inlet opening height to room height, room width to room height, and room depth to roo height may play important roles in generating 2D airflow. Fully to investigate the effects of differe inlet and room geometry were beyond the scope of the present experiment, however. Systemat validation of flow behaviour is thus necessary before the assumption of 2D flow is accepted a measurements are carried out in the symmetric plane only.

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References

ASHRAE (1997). ASHRAE handbook of fundamentals. American Society of Heating, Refrigerati and Air-Conditioning Engineers (ASHRAE), Atlanta, USA.

Becher P (1972). Varme og Ventilation (Heating and Ventilation), Vol 3, 4th Ed. Teknisk Forlag, Copenhage

Bjerg B; Morsing S; Svidt K; Zhang G (1999). Three-dimensional airflow in a livestock test room with two-dimensio boundary conditions. Journal of Agric. Engineering Research **74**(3), 267-274.

Förthmann, E (1934). Über turbulente Strahlausbreitung (Development of Turbulent Jets). Ing. Archiv 5.

Grimitlin M (1970). Zuluftverteilung in Räumen (Air distribution in rooms). Luft- und Kältetechnik, **5**:24 256.

Hoff S J; Janni K A; Jacobson L D (1995). Evaluating the performances of a low Reynold's numb turbulence model for describing mixed-flow airspeed and temperature distributions. The Transactio of the ASAE, **38**(5):1533-1541.

Nielsen P V (1974). Flow in air conditioned rooms (model experiments and solution of the fl equation). Ph.D. Thesis, Danish Technical University, Copenhagen.

Nielsen P V; Restivo A; Whitelaw J H (1978). The velocity characteristics of ventilated roon ASME Journal of fluid engineering, 100:291-298.

Nielsen P V; Möller Å T A (1988). Measurement on buoyant jet flows from a ceiling-mounted slot diffus The Third Seminar on "Application of Fluid Mechanics in Environmental Protection – 88". Silesian Techni University, Gliwice, Poland.

Nielsen P V (1990). Specification of a two-dimensional test case. International Energy Agency, Ener Conservation in Buildings and Community Systems, Annex 20: Air flow Pattern within Buildings.

Nielsen P V (1997). The Box Method – A Practical Procedure for Introduction of an Air Terminal Device CFD Calculation. Aalborg University, Aalborg, Denmark.

Timmons M B; Albright L D; Furry R B; Torrance K E (1986). Experimental and Numerical Stu of air movement in slot-ventilated enclosure. The Transactions of the ASHRAE, 92:221-239.

Verhoff A (1963). The Two-Dimensional Turbulent Wall Jet without an External Free Stream. Report No.6 Princeton University, Princeton, USA.

Zhang G; Morsing S (1994). Multi-head thermistor anemometer. Departmental Note, 1095-2. , Dan Institute of Agricultural Sciences, Dept.Ag.Eng., Research Centre Bygholm. Horsens, Denmark.