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Test Room for Validation of Airflow Patterns estimated by Computational Fluid Dynamics

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Symmetrical room geometry is not a sufficient condition for the design of a ventilated room where two-dimensional airflows are to be generated. Three-dimensional effects were observed in a symmetrically designed 3 m high by 5 m wide by 8·5 m long test room having a 0·019 m high slot inlet opening under the ceiling.

The attached jet velocity profile measured at the ceiling in the symmetrical centre plane agreed well with the theoretical calculations based on two-dimensional flow, but large differences were found away from the symmetrical centre plane. The velocities in the jet 4·5 m downstream from the inlet wall were up to twice as high on one side compared to 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, thus showing a semi-stable flow behaviour. The measured velocities in the symmetrical centre plane were only slightly affected by the switch-over and remained at the same level throughout the experiment. In both semi-stable conditions, the return air direction diverged 30° from the symmetrical plane.

Modification of the room with four 0·5 m high vertical guiding plates attached to the ceiling resulted in an acceptably uniform two-dimensional flow. The guiding plates changed the ceiling jet profile so it did not agree with the theoretical jet profile for an attached, two-dimensional flow. The maximum velocity became lower. At floor level, the direction of the return air was parallel to the symmetrical centre plane, without changes in the mean velocity.

Systematic validation of flow behaviour is thus necessary before the assumption of two-dimensional flow could be accepted and a study is carried out in the symmetrical plane only.

1. Introduction

The use of computational fluid dynamics (CFD) for analysis of airflow patterns in rooms has increased dramatically during the last 30 years (Launder & Spading, 1972; Nielsen, 1974; Choi *et al.*, 1988; Svidt, 1991; Hoff *et al.*, 1995; Harral & Boon, 1997). Experimental measurements using well-defined ventilated enclosures are recommended to validate the results of CFD simulations. The experimental enclosures can be scale models (Nielsen, 1974; Timmons *et al.*, 1986), or full-scale rooms (Hoff *et al.*, 1995). A commonly used design for a full-scale test room is a rectangular room with a slot inlet placed below the ceiling and a slot outlet near the floor (Timmons *et al.*, 1986; Hoff *et al.*, 1995). In such a room, two-dimensional (2-D) airflow patterns are assumed, and measurement data are taken in the symmetrical centre plane only. Few systematic experimental data are available, however, throughout well-defined, full-scale rooms to check the CFD code, analyse the boundary conditions and validate the mathematical algorithms.

Researchers working with indoor climate in livestock buildings have concluded that CFD is a promising tool for describing the overall airflow patterns and the

Notation

b	vertical distance from ceiling, m	x_o	horizontal distance from the inlet opening to the virtual origin of the jet, m
C_d	discharge coefficient	y	vertical height above floor, m
C_p	velocity decay constant of an attached, plane jet	u	air velocity in jet, m/s
erf	error function, defined as: $\mathrm{erf}(\sigma) = (2/\sqrt{\pi}) \int_0^{\sigma} \mathrm{e}^{-t^2}\, \mathrm{d}t$	u_o	air velocity at slot inlet opening, m/s
h	geometric height of slot inlet opening, m	u_x	maximum air velocity in jet at a distance x from the slot inlet opening, m/s
h_o	effective height of slot inlet opening, m	w	width of slot inlet opening, m
H	height of room space, m	W	width of room space, m
L	length of room space, m	z	horizontal distance from sidewall, m
Re	Reynolds number	δ	expansion coefficient of a jet, m/m
x	horizontal distance downstream from the inlet, m	ν	kinematic viscosity of inlet air, m^2/s

distribution of contaminants in livestock buildings (Timmons *et al*., 1986; Svidt, 1991; Hoff *et al*., 1995; Harral & Boon, 1997). However, inadequate information on the boundary conditions for animals, pen partitions, slatted floors, *etc*., which are specific for agricultural buildings, makes the results of the calculations uncertain. Simulations using CFD still depend on experimental data for model validation, modification, as well as definition of the boundary conditions.

A joint research project between the Royal Veterinary and Agricultural University (KVL), the Aalborg University (AAU) and the Danish Institute of Agricultural Sciences (DIAS) is focusing on the application of CFD in the analysis of air motion and velocity characteristics in livestock buildings. In the project, it was decided to build a full-scale experimental room that was gradually to be equipped with full-scale models of pigs, pen partitions and slatted floors. The intention was initially to validate algorithms for the simple situation of two-dimensional 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 symmetrical room was sufficient to achieve two-dimensional airflows. It turned out to be more difficult than expected. In this paper results of the experiments in the empty room are presented.

2. Jet models

The jet created by air supplied to a ventilated room space through a slot beneath the ceiling is generally referred to as an attached, plane jet. The characteristics of the jet are the primary factors affecting the airflow patterns in the room. At a distance downstream from the inlet the maximum velocity u_x in the jet can be estimated from standard two-dimensional jet algorithms (Grimitlin, 1970; ASHRAE, 1997):

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

where u_o is the inlet velocity, C_p is the velocity decay constant for a simple 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 an attached plane 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 can be estimated as $h_o = C_d\, h$, where C_d is the discharge coefficient and h the geometric height.

Normally, when the travelling distance of the jet is more than 25 times the inlet opening height, the velocity profiles follow the law of flow similarity for fully established turbulent flow (ASHRAE, 1997). That is, plotted in dimensionless form, the velocity profiles remain identical independent of the downstream distance. The dimensionless velocity ratio u/u_x in a cross-section at any distance from inlet could be described as (Verhoff, 1963)

$$\frac{u}{u_x} = 1{\cdot}481 \left[\frac{b}{\delta(x + x_o)} \right]^{1/7} \left(1 - \mathrm{erf}\left(0{\cdot}68\, \frac{b}{\delta(x + x_o)} \right) \right) \tag{2}$$

where $b = H - y$ is the vertical distance from the ceiling, 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 characterize the expansion of the jet.

The product $\delta(x + x_o)$ 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. For a narrow slot inlet opening without deflectors, as used in the experiments reported below, x_o can be ignored in Eqns (1) and (2).

Becher (1972) and ASHRAE (1997) suggested a simpler way to describe an attached, plane jet; the velocity profile could be half of a free expanding jet as shown in Eqn (3):

$$\left[\frac{b}{\delta(x + x_o)}\right]^2 = 3{\cdot}3 \log \frac{u_x}{u} \qquad (3)$$

Equation (3) can be rewritten as

$$\frac{u}{u_x} = 10^{-0{\cdot}3030[b/\delta(x+x_o)]^2} \qquad (4)$$

The velocity profile described by Eqn (4) is similar to the velocity profile described by Verhoff's equation Eqn (2), except within the thin boundary layer closest to the ceiling. Based on knowledge of δ, Eqns (2) and (4) may be used to calculate and compare ceiling jet profiles. In ventilated room spaces, a value of δ in the range between 0·06 and 0·14 is suggested, mainly depending on the room geometry, design of the inlet and the Reynolds number (Nielsen & Möller, 1988). Reynolds number is defined as $Re = u_o h_o / v$ where v is the kinematic viscosity of inlet air.

3. Material and methods

3.1. *Experimental room*

The experimental room was established in the Air Physic Laboratory (APL) at the Research Centre Bygholm. A description of the APL may be found in Morsing *et al.* (1995). The experimental room had a length L of 8·5 m, a height H of 3·0 m, and a width W of 5·0 m. A slot opening with a width w of 5 m equal to the width of the room ($w/W = 1$) was placed just below the ceiling. The height of the inlet slot was 0·1 m when fully open. The actual opening height could be adjusted within the range from 0 to 0·1 m with a 0·24 m bottom-hinged flap.

Similar dimensions were chosen for the experimental room as recommended for creating the two-dimensional flows (Nielsen, 1990). He suggested a room with a length of 9 m, a height of 3 m, and a width of 3·0 m with a full-width slot inlet with a height h of 0·168 m. The room dimensions were based on scale model experiments with two-dimensional flows. In this study, the height of the experimental room was kept at 3·0 m, but in order to create an experimental room which represented a weaning-pig section more realistically, the following adjustments were made.

(1) The width-to-height ratio W/H of the room was extended from 1·00 to 1·66.
(2) The length to height ratio L/H of the room was slightly reduced from 3·00 to 2·83.
(3) The exhaust system was placed in the floor beneath the inlet wall.
(4) In order to simulate cool weather conditions, the experiments were carried out with an inlet height h of 0·019 m. This gave an inlet to room height ratio h/H of 0·006, which is nearly a factor 10 smaller than suggested by Nielsen (1990).

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 1 m slatted floor 20% open, with exhaust to a below-floor channel beneath the inlet slot, *Fig. 1*. The cross-section of the channel was 0·6 m^2 spanning the width of the experimental room. To ensure uniform exhaust air distribution, the exhaust velocity was increased by partly covering the slatted floor with a plate, leaving 0·66 m^2 of slatted floor free as an outlet. A 4 m long duct, 0·5 m in diameter, connected the exhaust air to an airflow rate measurement orifice unit made according to ISO 5167-1 (1991). The estimated total uncertainty on the airflow rate was $\pm 3\%$. The room was made as airtight as possible, but to be sure that leakage did not affect the results, an air leakage test was carried out before any measurement and the measured flow rates corrected accordingly.

The geometric height of the inlet opening was adjusted to 0·019 m. The pressure difference across the inlet opening was set at 13·5 Pa, which is equivalent to a theoretical velocity of 4·75 m/s. An inlet airflow rate of 1300 m^3/h was obtained. On this basis, the calculated effective opening height h_o was 0·0152 m, and the discharge coefficient

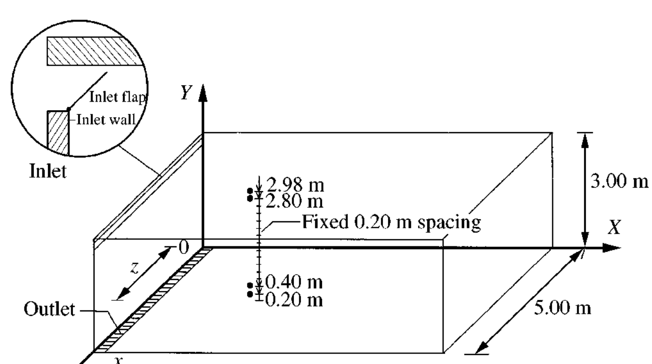

Fig. 1. Room geometry and positions of inlet, outlet and sensors. The horizontal distances x from the sensors to the inlet wall were 2·68, 3·50 and 4·50 m, and the horizontal distance z from the side-wall were 0·5, 1·5, 2·5, 3·5 and 4·5 m

0·8. At a supply air temperature, that was maintained at $20 \pm 1°C$, the kinematic viscosity was $1{\cdot}5 \times 10^{-5}\ m^2/s$ resulting in an *Re* of 4800. This was of the same order as used by Nielsen (1990).

3.2. *Measurements*

Velocity and temperature measurements were carried out with a multi-channel thermistor-based system. The velocity sensors were omnidirectional and connected to a personal computer via three SCXI1100 multiplexers and an MIO16-9 data acquisition board from National Instruments. The velocity and temperature measurement system is described in detail by Zhang and Morsing (1994). The temperature sensors were calibrated with a precision temperature measurement device, type F250 from Automatic Systems Laboratories. The velocity sensors were calibrated by placing them in the exit jet from an ISO nozzle using a Laser Doppler anemometer FlowLite from Dantec as the calibration reference equipment. The calibrations were made in the range between 0·1 and 6 m/s.

Fifteen sensors were placed in a vertical line on a fixture. The sensors were placed at a fixed spacing of 0·2 m except for the two sensors at the upper end, that could be slid up and down. The fixture was placed at two vertical levels, a low level with the bottom sensor 0·2 m above the floor and a high level with the bottom sensor 0·3 m above the floor. At the low level, the two upper sensors were 0·02 and 0·2 m from the ceiling. At the high level, the two upper sensors were placed 0·1 and 0·2 m from the ceiling. In so doing, data were recorded from 0·2 m above the floor to the ceiling in steps of 0·1 m plus one value recorded at a distance of 0·02 m from the ceiling. The vertical sensor positions with the fixture in the low level are given in *Fig. 1*.

The two vertical levels of the fixture resulted in 29 vertical measurement positions. The scan rate of the measurements was 10 Hz and the measurement time was 30 min with averaging every 5 min.

The fixture was placed at three downstream distances x of 2·68, 3·5, and 4·5 m from the inlet wall in planes at distances z of 0·5, 1·5, 2·5 (symmetrical plane), 3·5, and 4·5 m from the sidewall. Thus, the data were collected for the fixture in 15 horizontal positions.

4. Results

4.1. *Velocity profile in the symmetrical plane*

The measured velocities in the symmetrical plane are shown in *Fig. 2* at the three downstream distances x from the wall inlet. The velocities are presented in dimensionless form as the velocity ratio u/u_x as a function of the distance ratio from the ceiling b/x. The maximum air velocities u_x were estimated according to Eqn (1) using the value for x_o of 0 m, C_p of 3·8 and h_o of 0·016 m as stated previously.

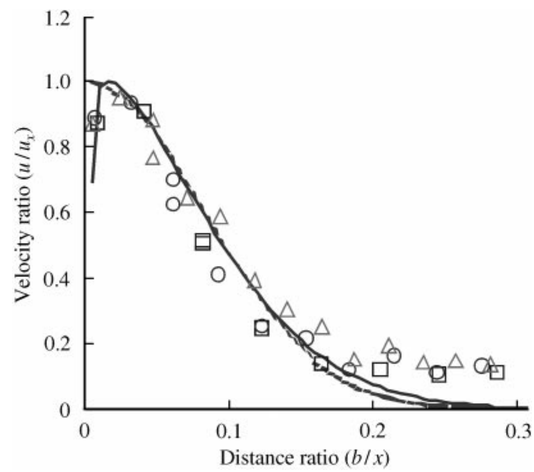

Fig. 2. Velocity profiles of the ceiling jet in the symmetrical plane at z of 2·5 m for the different values of the horizontal distance x downstream from the inlet: □, x of 2·68 m; ○, x of 3·5 m; △, x of 4·5 m; ▬▬, Eqn (2); – – –, Eqn (4); u, air velocity in jet; u_x, maximum air velocity in jet at distance x from inlet; b, vertical distance from ceiling

Both the velocity data in *Fig. 2* and smoke tests showed that jet velocities were confined within a distance ratio b/x of 0·2. On the basis of the velocity data in the jet the theoretical velocity profile was determined using non-linear parameter estimation of δ in Eqns (2) and (4). Only data from within the jet were included in the parameter estimation. The result was a value for δ of $0{\cdot}093 \pm 0{\cdot}0053$ m/m (95% confidence interval). In *Fig. 2*, the estimated profile for the jet, using Eqn (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 Eqn (4) gives the dotted line in *Fig. 2*, and the deviation near the ceiling is clearly seen.

4.2. *Two-dimensional airflow*

To check whether the airflow was two-dimensional or not the experimental data at a downstream distance x of 4·5 m from the inlet wall are used. The air velocity profiles in the planes at distances z of 0·5, 1·5, 2·5, 3·5 and 4·5 m from the sidewall are shown in *Fig. 3*. Together with the data the estimated profile is presented in the symmetrical plane according to Eqn (2) for comparison. It is seen that the velocity profiles on both sides of the

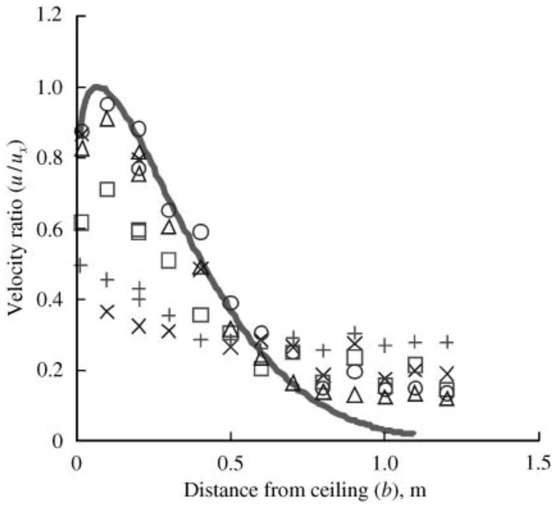

Fig. 3. Velocity profiles of the ceiling jet in five z-planes at the horizontal distance x of 4·5 m from the inlet wall: ×, *z of 0·5 m;* □, *z of 1·5 m;* ○, *z of 2·5 m;* △, *z of 3·5 m;* +, *z of 4·5 m;* ▬, *Eqn (2); u, air velocity in jet;* u_x, *maximum air velocity in jet at distance x from inlet; b, vertical distance from ceiling*

symmetrical plane were different from the velocities measured in the symmetrical plane. In general, the average velocities out of the symmetrical plane were lower.

The velocities measured outside the symmetrical plane were not in accordance with the traditional two-dimensional flow expectation, which assumes similar velocity profiles in all planes parallel to the symmetrical plane. To evaluate the findings, additional measurements were carried out. Six velocity sensors were placed 0·02 and 0·2 m below the ceiling at positions z of 0·5, 2·5 and 4·5 m from the sidewall. Continuous measurements were carried out for 8 h with a scan rate of 5 scans/s. Mean values were calculated and saved every 5 min.

The results from the sensors placed 0·2 m below the ceiling are shown in *Fig. 4*. In the full-scale, ventilated enclosure used in this research the velocities at one side of the symmetrical plane were up to twice as high as at 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, thus showing a semi-stable flow behaviour. The measured velocities in the symmetrical centre plane were only slightly affected 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 wind-vane was constructed. It was made of a low-friction wind-vane, originally developed for meteorological weather stations. In order to make it sensitive enough at very low velocities it was extended with a large vertical, lightweight plate 0·3 m by 0·25 m at the rear and a counterweight in the front. Recording of the direction of the return air was made at floor level in the centre plane 6·5 m from the inlet wall 0·2 m above the floor. In both semi-stable conditions the return air direction diverged 30° from the symmetrical plane, *Fig. 5*(*a*).

4.3. *Guiding plates*

To reduce the three-dimensional effect, four vertical guiding plates were installed under the ceiling, parallel to the inlet flow direction. The plates were 0·5 m high

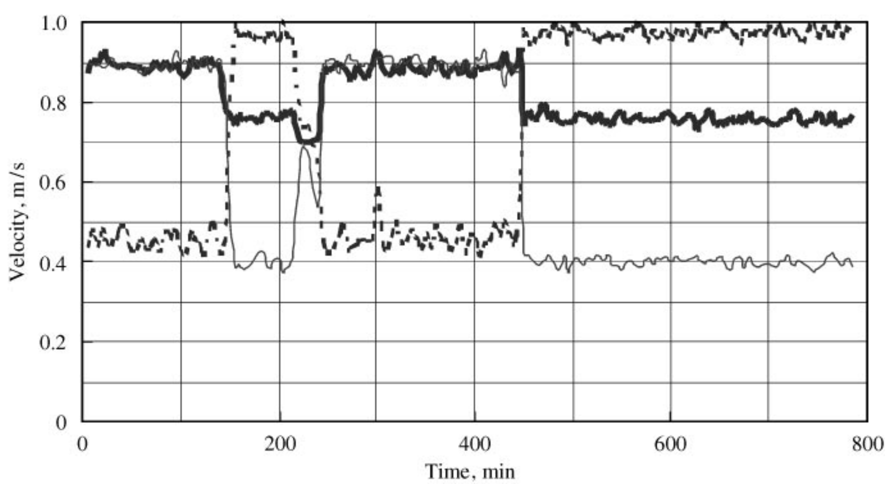

Fig. 4. Velocities measured in the ceiling jet at the distance x of 4.5 m from the inlet wall, a distance of 0·2 m from ceiling and at three distances z from the side-wall: – – –, *z of 0·5 m;* ▬, *z of 2·5 m;* —, *z of 4·5 m. The semi-stable airflow state in the room is clearly illustrated*

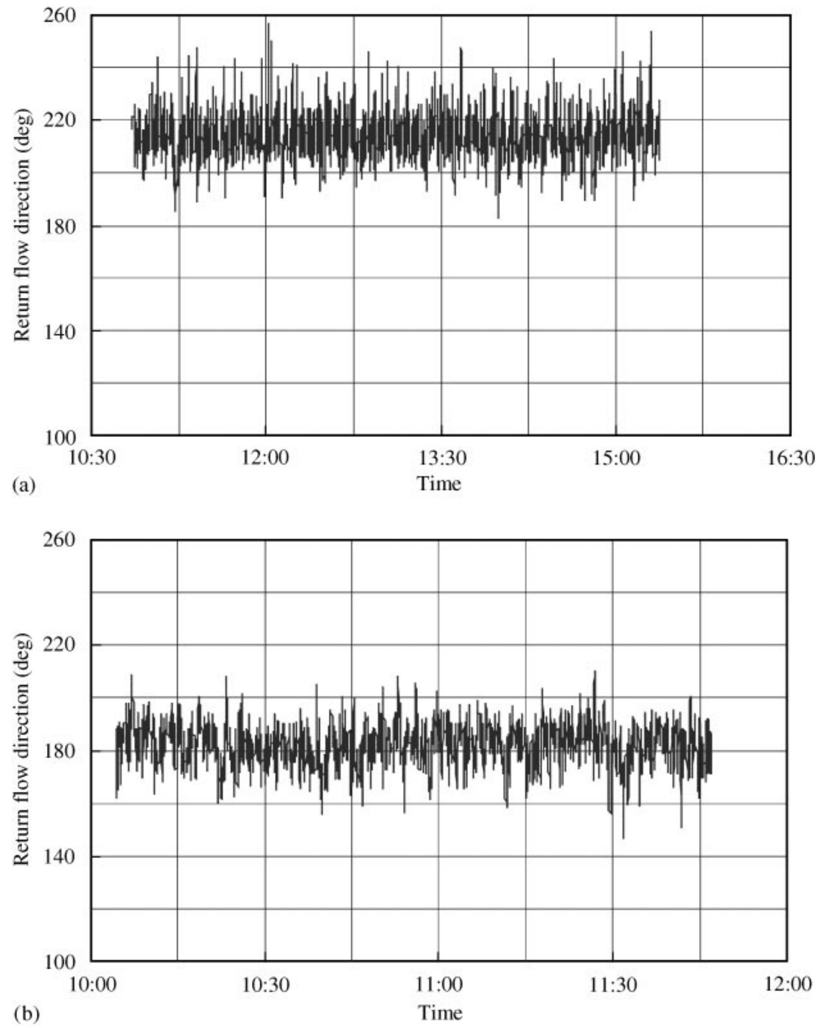

Fig. 5. Return airflow direction measured at x of 6·5 m, y of 0·2 m and z of 2·5 m, with and without ceiling guiding plates: (a) without ceiling guiding plates; (b) with ceiling guiding plates

starting 0·85 m from the inlet wall extending to the downstream end of the room. The design of the guiding plates is shown in *Fig. 6*. Additional measurements with the velocity sensor system were made in the z-plane 0·5, 1·5, 2·5, 3·5, and 4·5 m from the sidewall at a distance of 4.5 m downstream from the inlet wall. The results are shown in *Fig. 7*. The jet profiles became similar in all the five measurement planes parallel to the symmetrical centre plane. The direction of the return air at floor level measured with the low-velocity wind-vane became parallel with the symmetrical plane, *Fig. 5*(*b*).

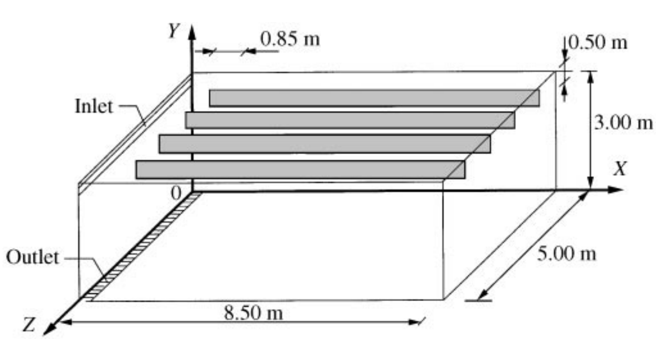

Fig. 6. The experimental room with ceiling guiding plates installed

It should be noticed, however, that the velocity profiles of the jet near the ceiling turned out to be different from the normal ceiling jet profiles. The maximum velocity became lower than estimated by using Eqn (2).

5. Discussion

It is surprising that the three-dimensional (3-D) flows encountered in this study were not explicitly reported in

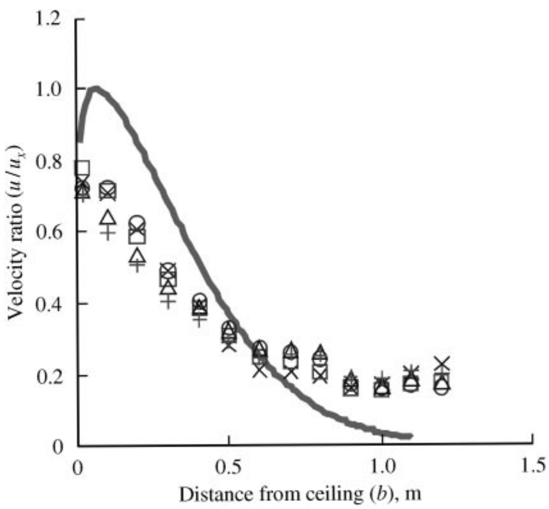

Fig. 7. Velocity profiles of the plane, attached jet at a distance x of 4·5 m downstream from the inlet wall in the room with guiding plates: ×, z of 0·5 m; □, z of 1·5 m; ○, z of 2·5 m, △, z of 3·5 m, +, z of 4·5 m; ▬▬, Eqn (2). air velocity in jet; u_x, maximum air velocity in jet at distance x from inlet; b, vertical distance from ceiling

many previous studies. Compared with the recommendation given by Nielsen (1990), the differences between the two test rooms were the ratio of the inlet opening height to room height h/H and the ratio of the room width to room height W/H may be the main reasons.

The h/H ratio used in this study was about ten times smaller than the one used by Nielsen (1990). The smaller ratio could be an important explanation for the 3-D flow. Karimipanah and Sandberg (1994) reported that at a downstream distance of 150 times the inlet height, momentum losses increase and momentum conservation is not valid. This means that the assumption of 2-D flows is questionable at larger distances from the inlet. The inlet opening height and inlet air velocity chosen in this study, however, were selected to represent practical system conditions of a weaning-pig room. Increasing the inlet opening height or the initial air velocity may reduce the 3-D effects, but this would result in too high a ventilation rate and too high an 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 two-dimensional flow is accepted and the measurements are carried out in the symmetrical plane only.

Three-dimensional 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 with a W/H ratio of 18 contains a periodical variation with a periodical interval of three times the room height. In the room with a W/H ratio of 1·67 the jet 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 W/H ratios larger than 1·67. However, in a test room with a W/H ratio equal to 1 and an L/H ratio of 3 no significant 3-D effects were found, neither in measurements (Nielsen *et al.*, 1978) nor in CFD-calculations (Bjerg *et al.*, 1999). Further investigations to examine the full effects of different inlet and room geometries were beyond the scope of the present experiment, however.

Ceiling guiding plates provided significant assistance in enabling the ceiling air jets and the return airflow in the experimental room to remain two-dimensional. A similar result was found in a 3-D CFD simulation (Bjerg, 1996). The optimum dimensions of the guiding plates, however, were not investigated in these studies.

6. Conclusions

Symmetrical room geometry is not a sufficient condition for the design of a ventilated room where two-dimensional airflows are to be generated. In the experimental room investigated the velocities on one side of the symmetrical plane were up to two times higher than on 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, thus showing a semi-stable flow behaviour. The measured velocities in the symmetrical centre plane were only slightly affected by this reversal and remained at the same level throughout the experiment. In both semi-stable conditions the return air direction diverged 30° from the symmetrical plane.

The ratios of inlet opening height to room height, room width to room height, and room length to room height may play important roles in generating two-dimensional airflows.

To reduce the three-dimensional effects four 0·5 m high vertical guiding plates were installed under the ceiling, parallel to the inlet flow direction. The jet profiles became similar in all the five measurement planes parallel to the symmetrical centre plane. The angle of the return air at floor level measured with the low-velocity wind-vane had become parallel with the symmetrical plane. It should be noted, however, that the velocity profiles of the jet near the ceiling turned out to be different from the normal ceiling jet profiles. The maximum velocity became lower.

Systematic validation of flow behaviour is thus necessary before the assumption of two-dimensional flow is accepted and measurements are carried out in the symmetrical plane only.

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