Obstacle Effects on Airflow and Contaminant Dispersion around a Naturally Ventilated Livestock Building

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Abstract

Naturally ventilated livestock buildings are widely used in agriculture due to the advantages of energy saving and absence of noise from mechanical ventilation. Today, one important issue concerning naturally ventilated buildings is the pollutant produced by the system and the resulting dispersion to the surrounding environment. The pollutant dispersion from a naturally ventilated building may, however, be affected by many factors. The objective of this research was to investigate airborne pollutant distribution in and around a naturally ventilated building with and without an upstream obstacle.

Experiments were performed in a wind tunnel using a scale model and numerical simulation was also performed. The results demonstrated that a solid obstacle located upstream of the windward sidewall of the scale model affected the velocity and contaminant concentration field in and around the building model. For this research, carbon dioxide (CO_2) was used as the contaminant. With the obstacle placed three times the ridge height (3H) upstream from the windward sidewall, the velocity field changed considerably compared to the case with no obstacle. Changing airflow patterns led to increased CO_2 concentration between the obstacle and the windward sidewall and lower CO_2 concentration downstream of the building.

Numerical simulations were performed with a full-scale building. The simulation results indicated the same trends for both the velocity field and CO_2 distribution. The simulated CO_2 concentrations downstream of the building were in fair agreement with the measured results at heights below 1H. The measured concentrations were slightly lower at a distance 2H downstream, however, and higher at a distance 4H compared with the simulated results. At both downstream distances, the simulation underestimated the concentrations at heights above 1.2H.

Keywords: natural ventilation, numerical simulation, velocity field, contaminant dispersion, wind obstacle

Introduction

Naturally ventilated livestock buildings are widely used in agriculture due to the advantages of energy saving and absence of noise from mechanical ventilation (Strøm and Morsing, 1984). Control and prediction of the environment inside a naturally ventilated building and the contaminant dispersion to the surroundings with the exhausted room air are still challenges to engineers for planning and design of the system (Strøm and Zhang, 1989). Wind induced natural ventilation may cause non-uniform airflow in the ventilated space.

During calm winter conditions, cold airflow from the inlet openings may directly reach the animal occupied zone. In order to overcome the poor controllability of the inlet jet and avoid cold air drafts, a concept of hybrid ventilation, which combines natural and mechanical ventilation with feed-forward control algorithms, was introduced (Zhang *et al.*, 1992). The hybrid ventilation system is operated as natural ventilation during most of the year and as mechanical ventilation in winter. Today, another important issue concerning buildings with natural and hybrid ventilation is the pollutant produced by the system and their effect on the surrounding environment. Understanding the pollutant dispersion around buildings may help to provide correct guidelines for building planning to avoid annoyance issues. The pollutant dispersion from an open type livestock building may, however, be affected by many factors.

The surroundings are important for building layout planning and ventilation control in order to take into account the effects of polluted air and odour transported from the livestock production building. Detailed knowledge is needed on how airflow and dispersion of contaminants are affected by wind and obstacles near buildings. Ikeguchi *et al.* (2003) reported experimental studies of the velocity field using a scale model in a wind tunnel with upstream obstacles consisting of a net, a solid wall or a building model. However, contaminants were not applied and the contaminant dispersion was predicted on the basis of the measured flow field. The objectives of the study reported in this paper were to investigate airborne pollutant distribution in and around a naturally ventilated building with and without an upstream obstacle by use of CO_2 as contaminant source and to compare the measurement results using scale models with numerical simulation.

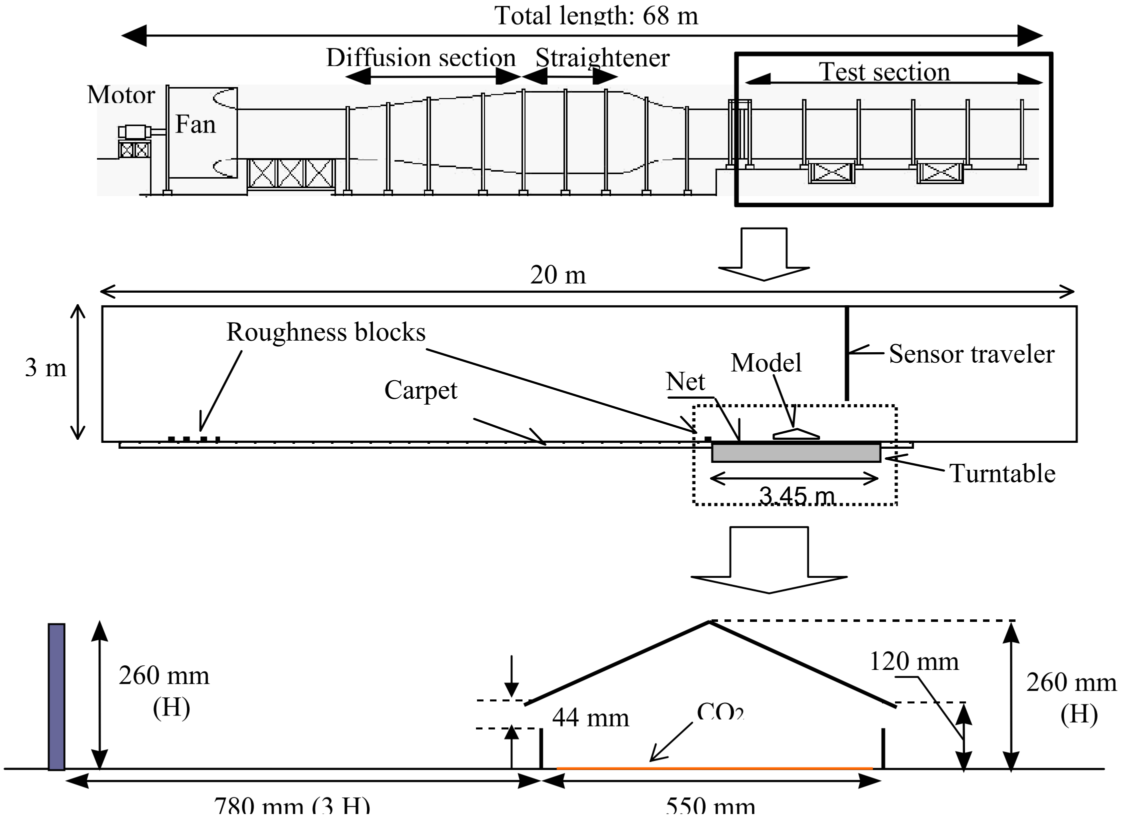


Figure 1. Wind tunnel used for experiments.

Materials and methods

Measurements

An investigation was carried out in a wind tunnel, with three scale models of a grow/finishing pig building, Figure 1.

The total length of the wind tunnel was 68 m. The test section of the wind tunnel was 20 m long, 4 m wide and 3 m high. Roughness blocks and surfaces were placed up-stream of the scale model in the test section in order to generate a wind profile similar to an agricultural field. Detailed information on the wind tunnel has been published by Ikeguchi and Okushima (2001) and Ikeguchi *et al.* (2003).

The three scale models were identical and placed on the floor in the testing section in a row perpendicular to the air stream. Each model was made of Plexiglas in scale 1:20 of a typical 11 m wide and 20 m long section of a Danish grower/finisher building with 2.6 m high sidewalls and 25° roof slope. The scale selected made the models small enough to avoid blocking effects in the wind tunnel and at the same time large enough to investigate wind effects on the inside air flow (Morsing *et al*., 2002). The outside dimensions of the models were thus 500 mm in length and 550 mm in width, eave height 130 mm and ridge height 260 mm. The solid part of the sidewall was 80 mm high leaving a slot-inlet opening height of 44 mm to the underside of the roof plate.

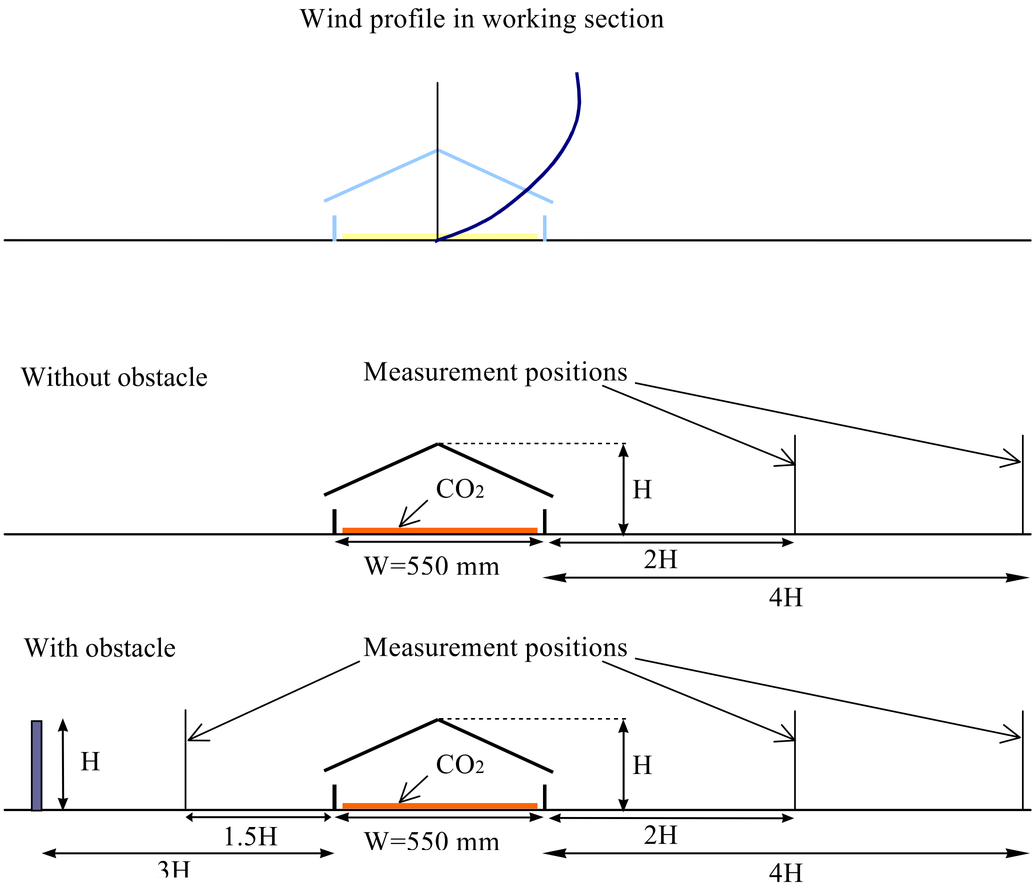


Figure 2. Experimental setup.

Four diffusion tubes made of soft nylon were symmetrically placed on the floor in the models central section to constantly supply CO_2 into the space at a rate of 5 liters per minute.

The wind profile measurement was carried out in the test section of the wind tunnel where the building model should be placed, Figure 2. The experiments were performed without any obstacle upstream of the model as a reference treatment and with a vertical, solid plate of height 1H (one times the model's height) placed 3H upstream from the windward sidewall. In order to make it easy to compare the results from scale model measurements and CFD simulations in full scale, the model height H was chosen as a reference length. The obstacle extended the whole width of the wind tunnel.

A multi-channel gas concentration measuring system with a built in infrared analyser, model ZAU, Fuji electric Inc., was used for CO_2 measurements. The instrument had an accuracy of 0.5%.

The concentrations were measured inside the middle model section and outside up- and downstream of the model. Background CO_2 in the wind air was measured 3.2 m upstream from the windward sidewall 0.62 m above the wind tunnel floor to avoid any possible effects that might be caused by diffusion and turbulent flow around the model. The vertical profiles of CO_2 concentration were measured by a five-point vertical sensor-array placed at 20 mm distances on a mobile fixture. The profiles were determined at downstream distances of 2H and 4H from the leeward sidewall as well as at an upstream distance of 1.5H from the windward sidewall to achieve knowledge of the effects on flow field and contaminant dispersion that might be caused by the obstacle.

Simulation

Numerical simulations were performed for a full-scale building, geometrically similar to the scale model. The program code used was CFD2000 version 3.3 from Adaptive Research (http://www.adaptive-research.com/). The k-e turbulence model (Launder and Spalding, 1974) was applied. The wind profile used as the boundary condition was the same as that achieved by the wind tunnel measurements. The friction function was used at all surfaces. The total number of cells was 48x40 in the symmetric plane for a 2D simulation. Velocity inlet with wind profile similar to the measurements was applied in the simulation.

Results and discussion

The wind profile in the centre of the experimental section of the wind tunnel is shown in *Figure 3*. The measured data fit well with the power function often used to describe wind profiles

$$u = u_{ref}\left(\frac{h}{h_{ref}}\right)^{\alpha} \qquad (1)$$

where, h is height above ground, u is velocity at height h; h_{ref} and u_{ref} are reference height and reference velocity respectively; α is the index of shear intensity. The regression result by curve fitting gave a value of 0.24 for the index α, which is similar with the index value generally used for wind profile in the agricultural field (SBI, 1981).

The background CO_2 concentration in the wind tunnel air was about 460 ppm but varied during the experimental period. Therefore relative values were used for data presentation and discussion. Within the model section it was about 2050 ppm for the case without obstacle and 2800 ppm with the obstacle.

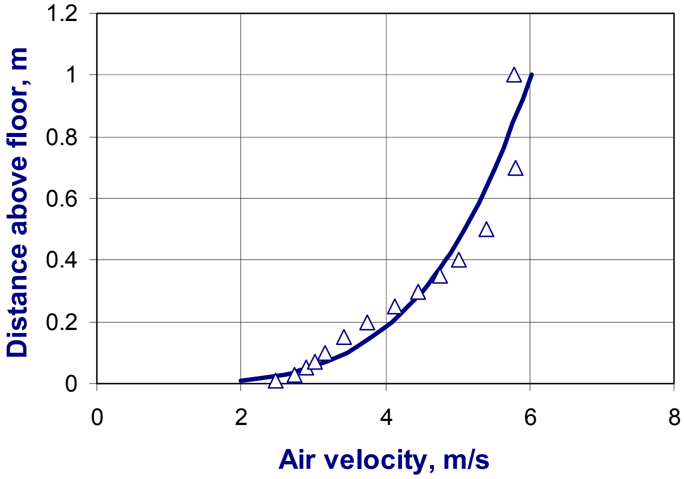
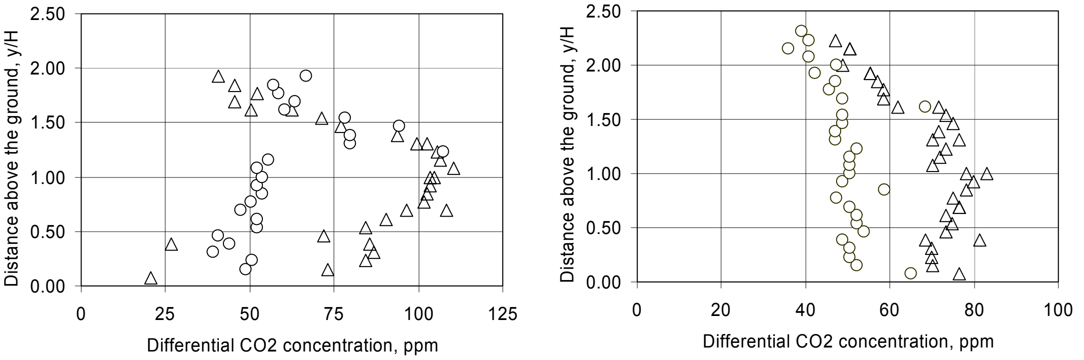


Figure 3. Wind profile in the working section of the wind tunnel without scale models and upstream obstacles in positions.

The results indicated that the upstream obstacle changed the ventilation rate. With the obstacle at 3H upstream the air exchange rate in the room space was reduced and the contaminant levels were increased compared to no obstacle.

The measured CO_2 concentration profiles at downstream distances 2H and 4H from the leeward sidewall of the scale model are shown in *Figures 4(a)* and *4(b)* respectively. For convenience of comparing with the simulation results, a dimensionless ratio y/H is used as the distance above the ground. The CO_2 concentrations are presented as the differences between the values at different positions and the background value. It is seen that for a given distance downstream, the differential CO_2 concentrations without the obstacle were higher than with the obstacle. In the case without the obstacle, the profile was similar to a plane jet with the maximum concentration at a height of 1H above the ground. The measured profiles were wider than expected using the central concentration decay.



(a) Distance 2H downstream *(b) Distance 4H downstream*

Figure 4. The differential CO_2 concentration at two distances downstream from the leeward sidewall, O, with obstacle and Δ without obstacle.

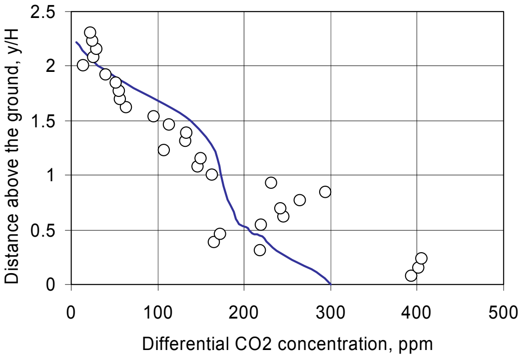


Figure 5. The differential CO_2 concentration at distance 1.5H upstream from the windward sidewall with obstacle, O*, measured data and* —*, numerical simulation.*

An interesting result was that higher CO_2 concentrations were measured between the obstacle and the model, *Figure 5*, at 1.5H upstream from the windward sidewall. The numerical simulation produced similar results in relation to CO_2 concentration and flow pattern around the building and the obstacle. Both measurement and simulation indicated that a large eddy between the obstacle and the scale model, *Figure 6*, influenced CO_2 diffusion and distribution. As a consequence, it affected the velocity field around the building as well as the inlet air velocity, which caused the differences in CO_2 dispersion and air exchange rates in the ventilated space. The result supports the prediction based on velocity field studies (Ikeguchi *et al.*, 2003).

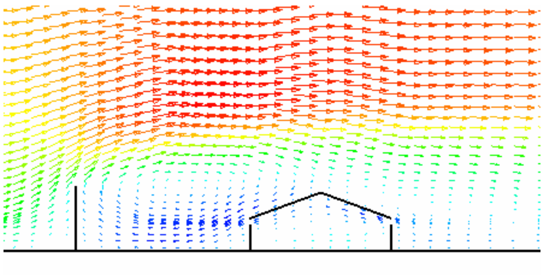
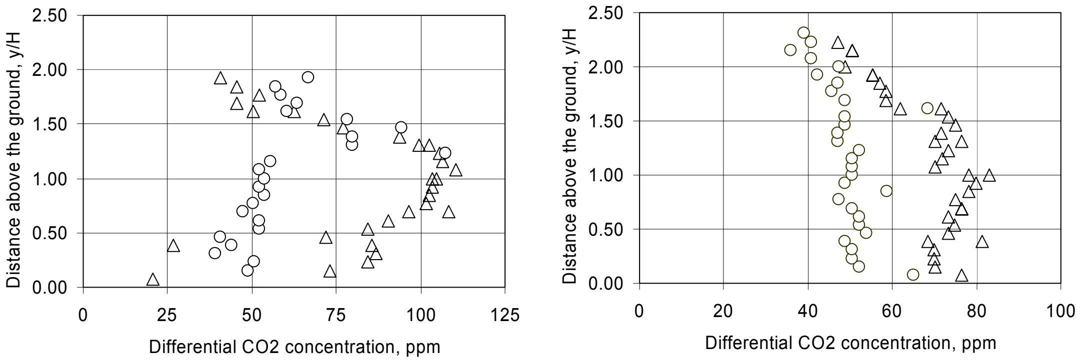


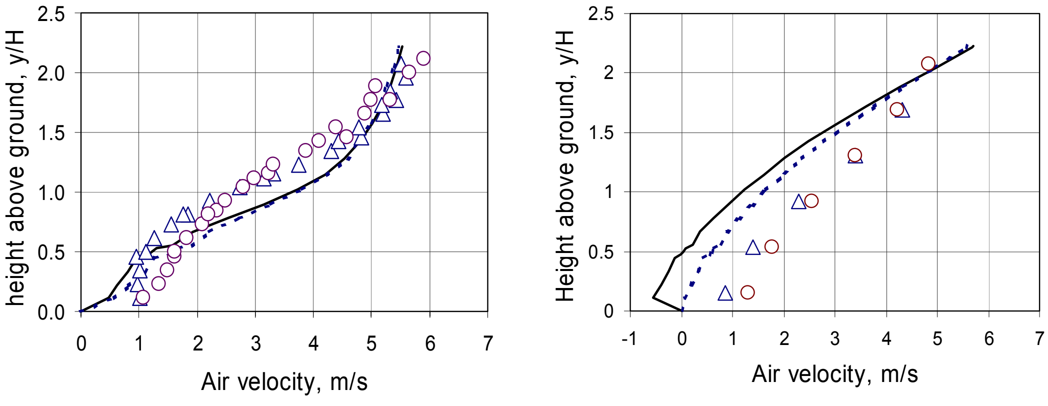
Figure 6. Airflow pattern achieved by the numerical simulation.

The simulation results compared to the measured data for the CO_2 concentration downstream with the obstacle are shown in *Figure 7*. The simulated CO_2 concentrations downstream of the building were in fair agreement with the measured results at heights below 1H. The measured concentrations were slightly lower at a distance 2H downstream, however, and higher at a distance 4H compared with the simulated results. At a distance 2H downstream, very high concentrations were measured at heights between 1.2H and 1.5H. These high concentrations were not found at a distance 4H downstream, where the measured concentrations varied smoothly in vertical direction. At both downstream distances, the simulation underestimated the concentrations at heights above 1.2H.



(a) Distance 2H downstream *(b) Distance 4H downstream*

Figure 7. Numerical simulation and measured data on the differential CO_2 concentration at two distances downstream with the upstream obstacle, where, O, *measured data and* —, *numerical simulation.*



(a) Without obstacle, *(b) With obstacle*

Figure 8. Velocity profiles downstream of the building without and with upstream obstacle, Δ*, measured at 2H;* O*, measured at 4H;* —*, simulation at 2H and* ---*, simulation at 4H.* .

Measured and simulated velocity profiles at 2H and 4H downstream from the leeward wall are shown in *Figures 8(a) and (b);* with and without the solid obstacle, respectively. The velocities measured with the obstacle were generally lower in the corresponding positions. At the building heights, the simulated velocity was over predicted without the obstacle and under predicted with the obstacle. At a downstream distance of 2H, the simulation result indicates that a return airflow exist at the height of up to 0.5H which was similar to the measured results by Ikeguchi *et al.* (2003), However, that was not demonstrated in this experiments.

The measured velocity between the obstacle and the building model is shown in *Figure 9*. The large variation in velocity values indicates that a recycle eddy exists between the obstacle and the building wall. That was validated by the CO_2 data and is in agreement with the numerical simulation, *Figure 6*.

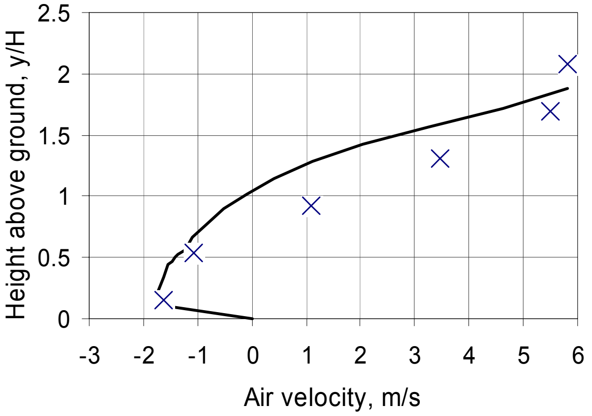


Figure 9. Velocity profile at 1.5H upstream from the windward inlet wall, ×*, measured data and solid line, numerical simulation.*

Conclusions

Obstacles located upstream of the windward sidewall of the scale model affected the velocity field in and around the building model, and consequently the CO_2 distribution.

With a solid obstacle placed 3H upstream from the windward sidewall, the velocity field was changed considerably compared to the case with no obstacle. Changing airflow patterns led to higher CO_2 concentrations between the obstacle and the building and lower CO_2 concentrations downwind of the leeward sidewall.

Numerical simulation was performed with a full-scale building. The simulation results indicated the same trends both for the velocity fields and CO_2 distribution. The simulated CO_2 concentrations downstream of the building were in fair agreement with the measured results at heights below 1H. The measured concentrations were slightly lower at a distance 2H downstream, however, and higher at a distance 4H compared with the simulated results. At both downstream distances, the simulation underestimated the concentrations at heights above 1.2H.

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