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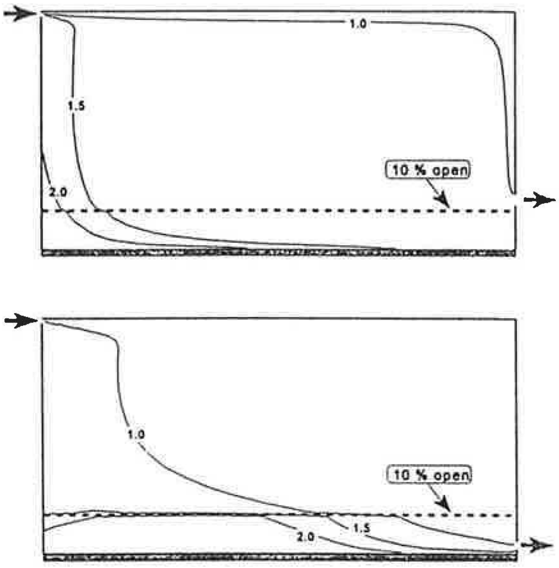

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COMPUTER PREDICTION OF AIR QUALITY IN LIVESTOCK BUILDINGS

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Computer Prediction of Air Quality in Livestock Buildings

Abstract

In modern livestock buildings the design of ventilation systems is important in order to obtain good air quality. The use of Computational Fluid Dynamics for predicting the air distribution makes it possible to include the effect of room geometry and heat sources in the design process. This paper presents numerical prediction of air flow in a livestock building compared with laboratory measurements. An example of the calculation of contaminant distribution is given, and the future possibilities of the method are discussed.

Introduction

Since the 1970's livestock production systems have been developed towards larger and more industrialized systems. Today, the production of poultry and pigs is mainly based on indoor production with mechanical ventilation and a relatively large number of animals per unit area. In these systems it is often a problem to keep the indoor air quality at a satisfactory level. A number of investigations have shown that high levels of dust and gaseous contaminants cause respiratory problems for the farmers as well as for the animals (see, e.g. Hjort 1990, Bækbo 1989).

The recorded problems demonstrate, that there is a need for better design tools which can include air quality as an important parameter in the design of the building and the ventilation system. Traditional methods for calculating air distribution in farm buildings are mainly based on semi-empirical equations describing isolated flow elements, such as free jets or wall jets. These methods cannot include the effect of room geometry or the effect of obstacles on airflow patterns, and they provide no possibilities to calculate important parameters such as contaminant concentration and ventilation efficiency for the ventilation system.

Computational Fluid Dynamics (CFD) is a technique which can be used for a detailed computer prediction of air velocities and temperature distribution in a ventilated space. In principle, the ventilated space is divided into a large number of small control volumes. In each control volume the local air velocity, pressure and temperature are calculated (Nielsen 1974, 1994, Christensen 1991). The solution is determined by the boundary conditions which include room geometry, position of air inlet and outlet, inlet air velocity and air temperature and position of heat sources and obstacles. Once the airflow field has been described in this way, it is possible to calculate the contaminant distribution in the room provided boundary conditions for the contaminant sources are known.

Since the CFD-technique demands very powerful computers compared with other methods, it has not been used widely until a few years ago when desktop computers with sufficient capacity were introduced.

Theoretical basis

The airflow in a room can be described by a set of partial differential equations, the Navier-Stokes equations which can be written in the following general form:

$$\rho\left(u_j \frac{\partial \phi}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\left(\mu_l + \mu_t\right)\frac{\partial \phi}{\partial x_j}\right) + S_\phi \qquad (1)$$

where subscript j can take the values 1, 2, 3 denoting the three space coordinates. The left-hand side of eq. (1) represents convection and the right-hand side represents diffusion and source terms. Schlichting (1979) gives a detailed description of the governing equations.

The turbulent viscosity μ_t describes the effects of turbulence on the airflow. The local value of the turbulent viscosity should be determined in each point of the solution domain by a turbulence model. Rodi (1984) describes the principles of different turbulence models. In the present study the standard k,ϵ turbulence model was used, in which the local value of turbulent viscosity is defined as:

$$\mu_t = \rho c_\mu \frac{k^2}{\epsilon} \qquad (2)$$

Like air velocities and air temperature the variables k and ϵ should be calculated in each point of the solution domain, based on equations of the same type as eq. (1) with different source terms. After the introduction of these variables the equation system to be solved consists of seven partial differential equations with seven unknowns. The unknowns are the velocities u, v and w, air pressure p, temperature T, and the turbulent quantities k and ϵ. Techniques for numerical solution of the equations are described by Patankar 1980.

Air quality, i.e. the concentration of gaseous or particulate contaminants, can be calculated when the velocity and temperature fields have been solved. This is based on the assumption that the contaminant concentration or the mass fraction of particles do not affect the velocity field. The equation for a gaseous contaminant is similar to the temperature equation and therefore easy to incorporate in a standard CFD-code but only a few authors (e.g. Rom 1995, Aarnink et.al. 1996) have presented measurements suitable as boundary conditions. Particles are much more complicated to handle since particle size, gravity, coagulation, adhesion to surfaces etc. should be taken into account. The modelling of particles has been studied by Gustafsson 1988, Maghirang & Manbeck 1993, Madsen 1994 and Andersen 1995.

Nomenclature

ρ	is the air density
u_1	is the velocity in the x - direction
u_2	is the velocity in the y - direction
u_3	is the velocity in the z - direction
S_ϕ	is a source term of the variable ϕ
ϕ	represents any of the variables to be solved
μ_l	is the constant laminar viscosity of the air
μ_t	is the turbulent viscosity of the air
c_μ	is an empirical constant
k	is the turbulent kinetic energy
ϵ	is the dissipation of turbulent kinetic energy

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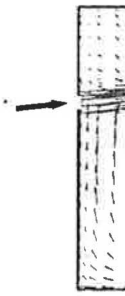

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Verification of calculated velocity fields

Before the contaminant distribution can be calculated, the correct velocity field must be known. Figure 1 shows an example of a calculated velocity field in a laboratory set-up with a commercial type inlet device. An air flow rate of 375 m^3/h is supplied at 1.9 m/s and a temperature which is 10 °C below the room temperature. The modelling of the inlet boundary conditions has been described by Svidt 1994a. The trajectory of the jet has been defined as the path of the point of maximum velocity in the jet. Figure 2 shows a good agreement between the calculated trajectory and a measured trajectory based on full-scale laboratory measurements (Svidt 1994b).

Results on figure 1 and 2 are based on an evenly distributed heat source on the entire floor area. In the next case, the inlet has been changed to a smaller inlet area and a larger inlet velocity, so that the inlet air jet attaches to the ceiling. In addition the heat source is changed to cover only one half of the floor area which gives a very asymmetric heat production. The experiments and the simulations show, that the attached ceiling jet is strongly affected by the asymmetric heat source. Figure 3 shows a top view of the calculated flow field immediately below the ceiling. It is seen how the jet develops semi-radially from the point of impingement and it is forced to one side of the room. The measured and calculated velocity profile at the dashed line are compared in figure 4.

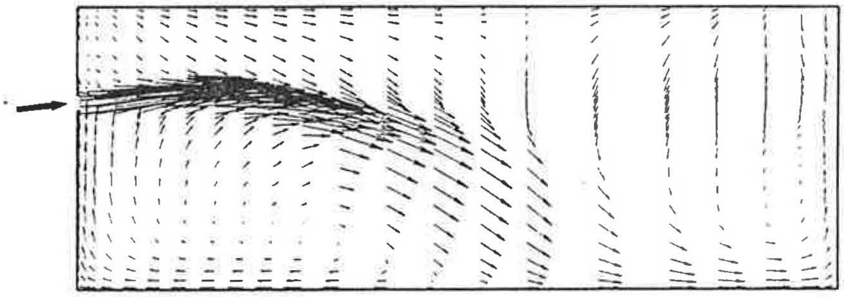

Figure 1. Three-dimensional calculation of the thermal airflow in a room with a commercial type inlet device. The figure shows a section at the centre of the inlet device.

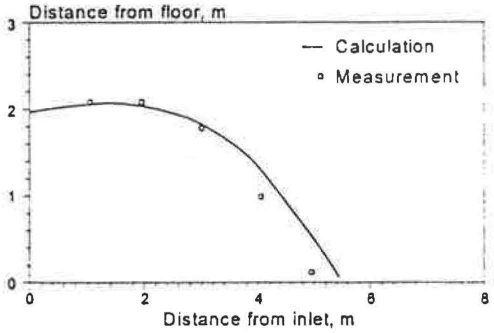

Figure 2. A comparison of the measured and calculated trajectory of the jet shown in figure 1.

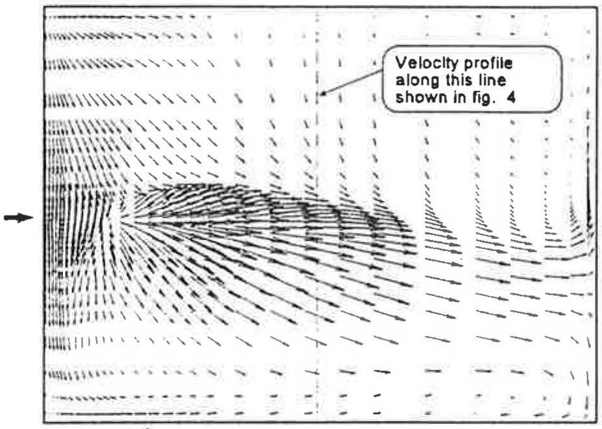

Figure 3. Calculated flow field near the ceiling for an attached ceiling jet affected by an asymmetrical heat source.

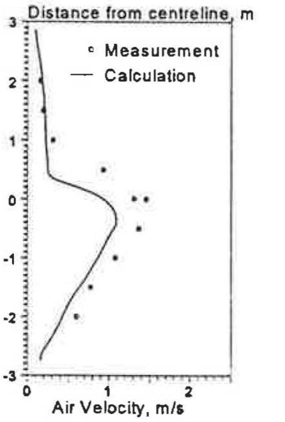

Figure 4. Velocity profile of the attached ceiling jet.

Calculation of contaminant distribution in a livestock building

This section shows some simplified examples to demonstrate how computer prediction of air velocities and contaminant distribution can be used to evaluate the consequences of different solutions in the design process. The examples are based on two-dimensional, isothermal simulations. The case is a building with a fully slatted floor.

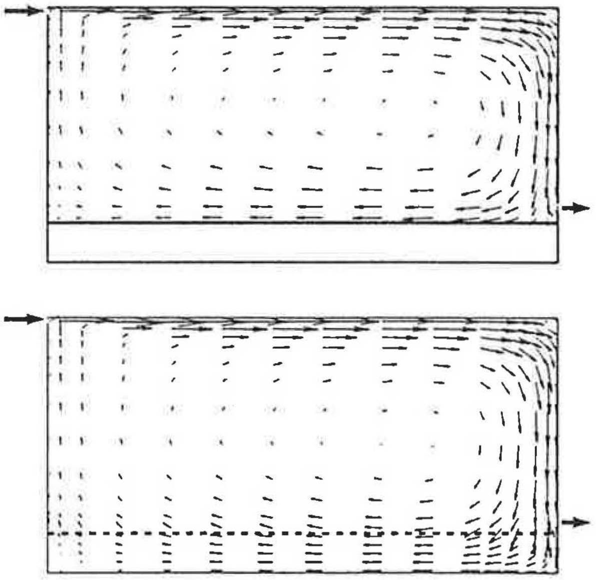

Figure 5. Calculated flow field in case of solid floor and a slatted floor with an opening area of 30 %. Bold arrows indicate air inlet and exhaust.

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Figure 5 shows a comparison of the flow in a building with solid floor and a building with a fully slatted floor where the opening area is assumed to be 30% of the total floor area. The calculated flow field shows, that the space below the slatted floor forms an integrated part of the ventilated space. This implies that gaseous contaminants released here may be transported to the occupied zone by the recirculating airflow.

Before studying the details of the contaminant distribution we shall look at changes in the velocity distribution caused by the slatted floor. Figure 6 shows that the slatted floor may reduce the velocity level in the occupied zone. In the case with a solid floor there is a large area in the near-floor region with air velocities greater than 15% of the inlet velocity. In the case with slatted floor this area is smaller and it is found below the floor.

Contaminant concentrations are studied in figures 7 and 8. It is assumed that a contaminant is released at a constant rate from a surface 0.4 m below the slatted floor. Concentration levels are normalized with the exhaust concentration, i.e. a concentration level of 1.0 is the concentration that would be in a situation with completely mixed air. The upper part of figure 7 corresponds to the flow field described in figures 5 and 6. The recirculating flow transports contaminant to the occupied zone in the left-hand side of the figure causing concentration levels higher than 1.5 times the exhaust concentration. In most of the occupied zone the concentrtion level is between 1.0 and 1.5. Since all of the contaminant is released below the slatted floor it would be obvious to move the exhaust to this region in order to reduce the contaminant level in the occupied zone. The lower part of figure 7 shows that this solution only results in minor changes to the contaminant distribution. Most of the occupied zone still has a concentration level between 1 and 1.5. This is due to the relatively high free area ratio of the slatted floor which causes that a low

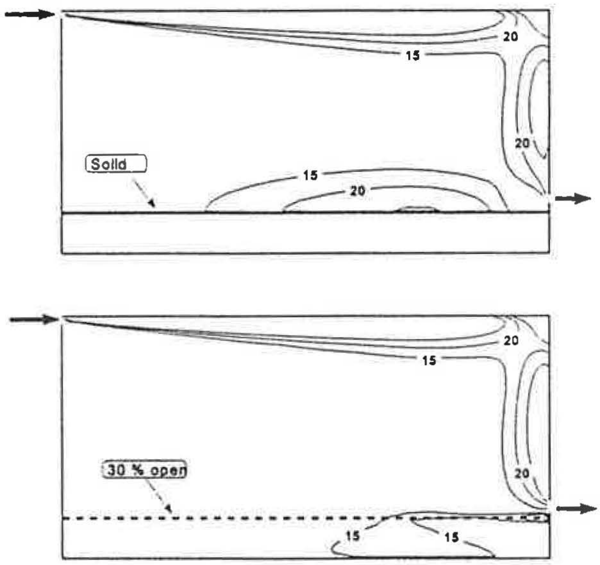

Figure 6. The calculated velocity distribution in case of solid and slatted floor. Numbers on the isovels specify the air velocity in percent of the inlet velocity.

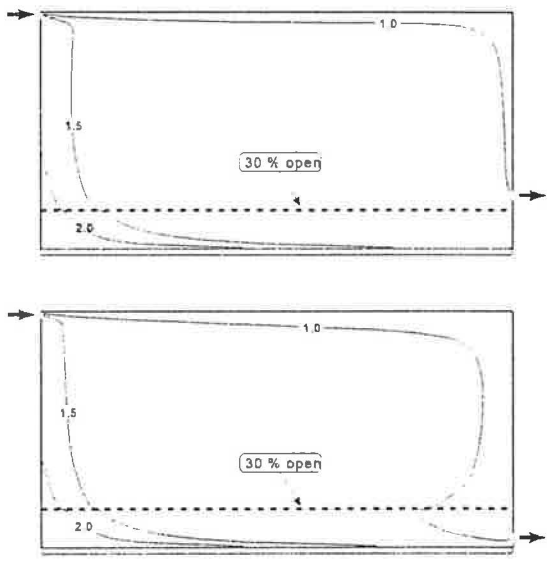

Figure 7. Calculated contaminant concentrations in the room with the air exhaust above the slatted floor and below the slatted floor, respectively. The free area ratio of the slatted floor is 30 %.

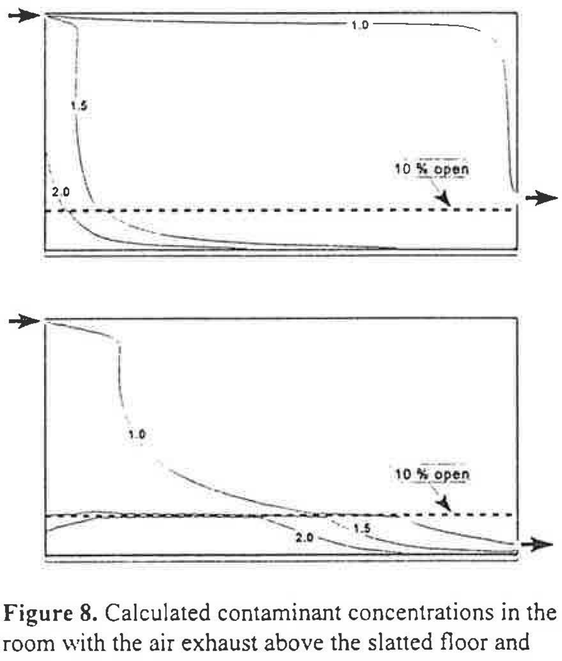

Figure 8. Calculated contaminant concentrations in the room with the air exhaust above the slatted floor and below the slatted floor, resopectively. The slatted floor has a free area ratio of 10%.

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pressure zone cannot be established below the floor. This situation can be changed by a reduction of the free area ratio of the slatted floor. In figure 8 the opening area of the slatted floor is reduced from 30% to 10%. This has a distinct effect on the calculated contaminant distribution when the exhaust is placed below the slatted floor. In this case the contaminant concentration is less than 1.0 in a large part of the occupied zone.

Discussion and conclusions

The example presented above shows that there are some interesting possibilities in computer prediction of the air quality in livestock buildings. It may become a powerful tool to evaluate new ideas or different options in the design process of new buildings or buildings to be renovated.

It must, however, be accentuated that the example is based on some great simplifications. In a real-life situation there will normally be a three-dimensional geometry including building details, equipment and animals that affect the airflow and in addition thermal effects have a significant influence on the airflow in a livestock building. The boundary condition for the contaminant source has been modelled as a constant rate from the entire surface below the slatted floor. In practice contaminants would be released from a number of positions above and below the slatted floor. The release rate would be varying in time and depend on local air velocities and temperatures, choice of feed, production management etc.

Some of the problems in computer prediction of airflow and contaminant distribution in livestock buildings are common to other applications of CFD in ventilation, i.e. ventilation in industrial buildings, shopping malls, offices etc. and hence a wider range of researchers and software developers are working on these problems.

Other problems are very specific to the agricultural field so agricultural researchers should pay special attention to them. This is especially the case for the modelling of contaminant sources in livestock buildings where detailed measurements of contaminant release rates under different conditions are needed as boundary conditions for the computer models.

Acknowledgements

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