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Numerical Modelling of Aerial Pollutant Emissions in and from Livestock Buildings

VOLKER CASPARY, TORSTEN HINZ, KARL-HEINZ KRAUSE and STEFAN LINKE

Institute of Technology and Biosystems Engineering

1 Introduction

The production and emission of airborne contaminants, heat and moisture are important factors in animal production, because they determine indoor air hygiene, environmental pollution and nuisance. The complex sources and transport phenomena involved in livestock buildings make a critical assessment of different control strategies and of their optimization diffcult. Evaluation of models relating air movement and building geometry by experimental studies is costly, not only in equipment and manpower, but also in time, because not all the parameters can be changed readily. Physical modelling, especially on a small scale, has traditionally provided a means of evaluating practical problems, although in some cases cost and timescale preclude even its use. The use of numerical models potentially offers a further saving in resources.

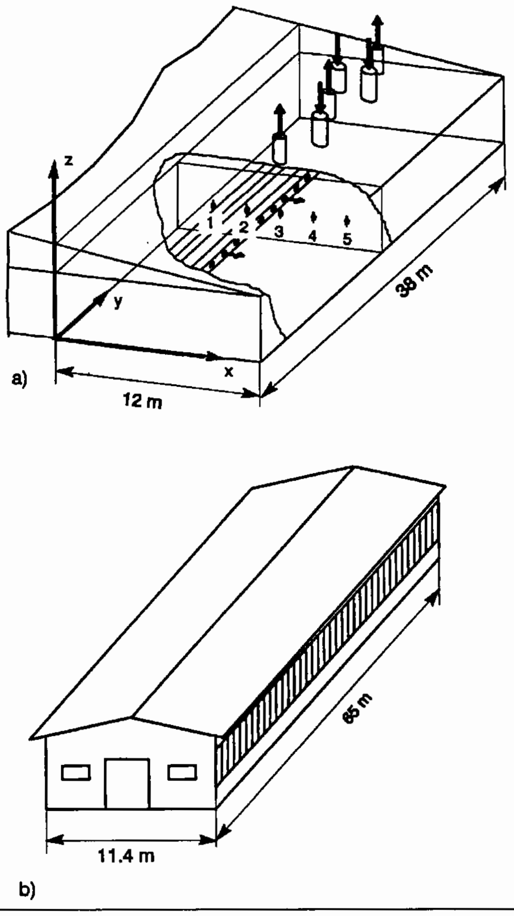

Fig. 1: Schemes of the two buildings studied
a) Force-ventilated fattening piggery at Vechta
b) Naturally-ventilated Louisiana-type broiler house at Verden

In this paper, the results are given of applying different numerical models to predict the distribution of gaseous contaminants inside a force-ventilated fattening piggery (**Figure 1a**) and inside a naturally-ventilated Louisiana-type broiler house (**Figure 1b**). The same two buildings were used in a related comprehensive experimental study. For the former building, the distribution of ammonia concentrations around the building was also modelled. To validate the numerical model, computed and experimental results from the piggery were compared using a scale model.

The objectives of this study were not only to gain knowledge about pollutant distribution inside and outside livestock buildings, but also to support the related compresensive studies [1, 2], by assessing how representative are different measuring positions in experimental (field) studies.

2 The numerical models used

Different numerical models were selected according to the task. For predictions of air flow inside the piggery (Figure 1a), which were made at both 1/25 scale and full size, the numerical models were those described by CASPARY [3]. The Flow 3D programme [4] was also used, for calculating ammonia concentrations inside the Louisiana-type broiler house (Figure 1b).

For dispersion around the outside of piggery, a Gaussian model was used [5], which considered emission classes and the frequency distribution of different emission situations. The Flow 3D programme [4] was also used for calculating ammonia concentrations downwind of the fattening piggery over a short range.

3 Results inside buildings

3.1 The force-ventilated fattening piggery

In addition to the numerical study using a 1/25 scale model of the fattening piggery [3], a three dimensional investigation of the same piggery at full scale, was performed. At full scale, the flow pattern was, however, much more complex, because of the ventilation arrangement,

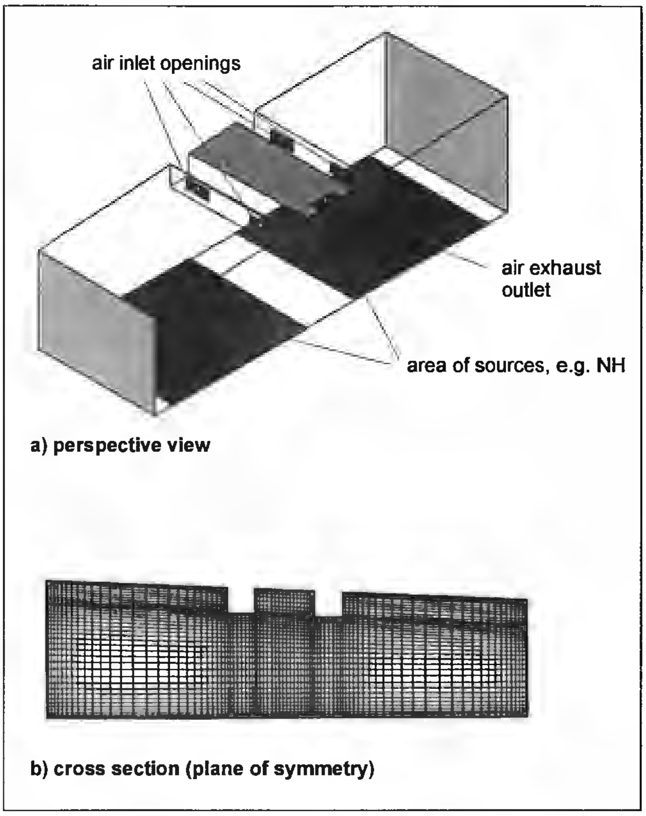

Fig. 2: Boundary definition for full scale modelling of the fattening piggery shown by a) perspective view and b) cross section

which was characterized by discrete air inlet openings equally distributed over the whole length of a fresh air duct (see Figure 1a), as well as by turbulent motion. Thus, more severe restrictions on space discretization and numerical integration procedure were required for the fullscale case, because stability problems occurred more often than with the 1/25 scale case [6, 7]. To improve the stability of the numerical calculation procedure and to guarantee a sufficient accuracy in regions of strong spatial gradients, it was necessary to optimize the mesh structure and ensure a smooth transition between the near wall fine grid and the inner coarse grid. Mesh optimization, however, is always accompanied by a requirement for an increasing number of cells. Against this, if the ventilation system has one or more planes of symmetric then the amount of computation can be reduced.

As seen from Figure 1a, for the force-ventilated piggery in question, symmetry allows the calculation domain to be limited to one section of the five which exist in the building. Calculations were performed by making use of the system of Eulerian coordinates shown in Figure 1a, but applied to a domain comprising the piggery's full x and z dimensions but only one fifth of its full y dimension (see **Figure 2**). By exploiting this symmetry of the ventilation arrangement, the numerical model could be run on a 64 MB RAM workstation.

The calculations, however, showed a slight tendency to oscillations. The fluctuations were caused by the occurence of recirculation zones generating numerical disturbance within the planes of symmetry. An analysis of the flow field showed that the zones generating numerical oscillation were confined to small areas located at all four vertices close to the top of the model. Thus, the influence of the disturbance was expected to be quite low, and this was confirmed by plotting the variation with horizontal distance, of velocity within an incoming air jet after different numbers of iterations of the calculation procedure (see **Figure 3**). The deviation between the calculated velocities after 450 and after 1000 iterations was no more than the order of magnitude of the accuracy of the measured velocities, which are also presented in Figure 3.

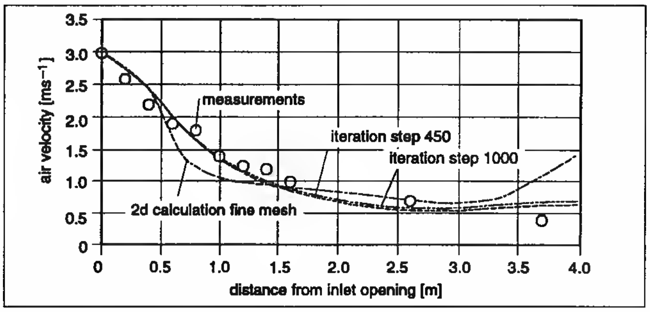

Fig. 3: Comparison of measured and calculated air inlet velocity in the fattening piggery

Although the two-dimensional model had achieved reasonable predictions when applied to the 1/25 scale building, this was not the case with the full scale building. Here it predicted only poorly the air velocity within the incoming free jet (see Figure 3), since strong three dimensional flow patterns were generated by the ventilation system with its four discrete air inlet openings and one air outlet opening per domain (Figure 2). Calculating a reasonable flow pattern is of course the basis for realistic prediction of contaminant distribution.

The numerical studies of the scale 1/25 model showed only a slight influence of the end walls on the flow pattern within the model chamber. Thus, the quality of the calculation performed by applying the space discretization and boundary conditions as shown in Figure 2, was assessed with regard to the influence of a wall boundary on the flow pattern. Three calculation domains were combined in a new mesh for numerical calculation, to study the influence of the side walls and of different ventilation conditions. Instead of using two planes of symmetry, the application of one plane of symmetry and one wall boundary leads to a three dimensional calculation within a geometry as presented in **Figure 4**. For comparison, the air velocity and the concentration of carbon dioxide were extracted from the three dimensional field of transport quantities at seven sensor locations in the cross section as marked in Figure 4. Locations 1, 2 and 3 are, respectiveliy, one quarter, one half and three quarters of the way across the width of the piggery. Locations 4 to 6 are vertically above locations 1 or 3, respectively. Location 7 is placed close to the air outlet opening. In order to obtain a symmetric solution in the three dimensional case, the volumetric flows through all three outlet openings were taken to be identical, and generation of carbon dioxide was assumed to be uniform throughout the area of sources on the floor of the room. Thus, only the complication of the disturbance due to the end wall was added to the numerical problem. Even so, the memory requirement for running the program increased to at least 196 MB RAM without making use of hard disk swap space.

When the air flow rate through all five exhaust fans was identical ("Ventilation Condition 1": see below), the influence of the walls on the predicted air flow and on the distribution of pollutant concentrations was quite small, as shown in **Figure 5**, which shows both the parameters plotted over the building's width at the sensor locations 4, 6 and 7. In Figure 5, the symbols mark the sensor locations for the two-dimensional calculation based on one domain as shown in Figure 2 and the dashed lines shows the results of the three dimensional calculation based on the geometry shown in Figure 4. The symmetry constraint is maintained over most of the building, and therefore there is only a relatively small influence of the wall on the internal transport phenomena (see Figure 5). Only in the vicinity of the side wall is a discrepancy between the predictions of the two-dimensional and three-dimensional calculations apparent. In the case of the three-dimensional computation, the concentration of carbon dioxide increases in this area; an effect which is impossible to resolve with two-dimensional calculations performed in one domain as shown in Figure 2.

Additional three-dimensional studies were performed to facilitate investigations of the influence of different ventilation conditions on the internal transport phenomena. The simulation thereby becomes more realistic, because the ventilation system in that piggery mainly uses the end-most outlet fans for temperature regulation through variation of the volume flow rate [2]. This has a strong influence on the internal flow field as can be seen in **Figure 6** where the trajectories of massless particles are shown for two different ventilation conditions. For "Ventilation Condition 1", the air flow rate through the end-most and the middle exhaust fans is the same. In "Ventilation Condition 2", the air flow rate through exhaust fan 2 is a quarter of that through each of exhaust fans 1 and 3. In Figure 6, a strong influence of a different distribution of exhaust air flow is visible: the particles tend to move to those air outlet openings which have the higher exhaust rate. In **Figure 7**, the calculated concentration field is plotted versus the building's width, to compare the concentration fields from the two different ventilation conditions. Figure 7 shows a predicted increase in concentration as the side wall is approached. In the experimental studies, measurements of the concentration of carbon dioxide were carried out in the middle of the piggery at the location of sensor 2, a distance of 1 m from the end wall. At this location the predicted concentration was 1170 ppm which differs by about 5 % from the observed concentration of 1238 ppm, obtained by time-averaging over a period of one day.

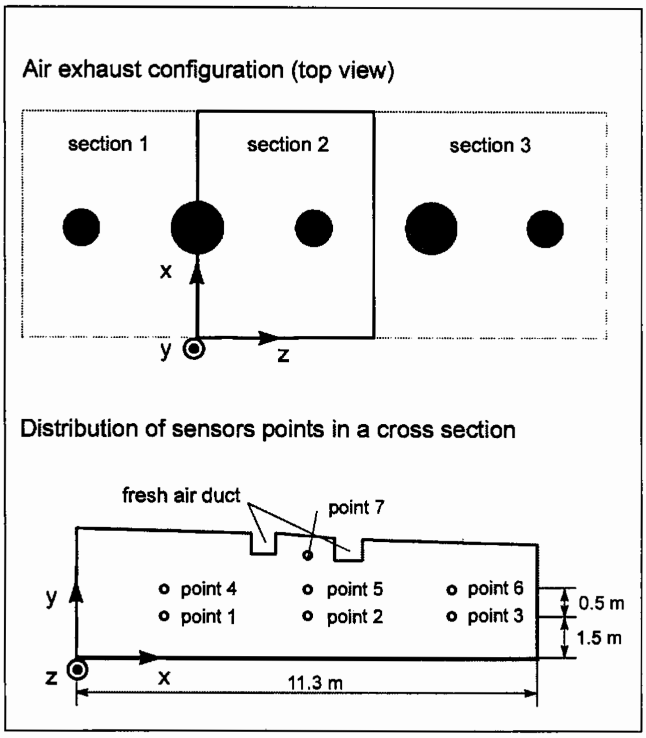

Fig. 4: Air exhaust configuration and sensor point locations for discretized geometry used for three dimensional calculations for the fattening piggery

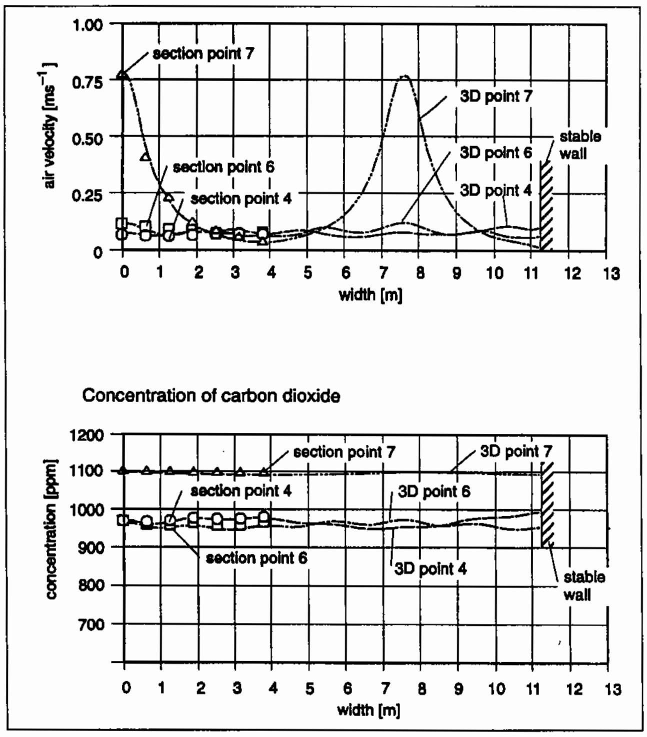

Fig. 5: Comparison of predictions from calculation performed in a section of the piggery with a three-dimensional calculation

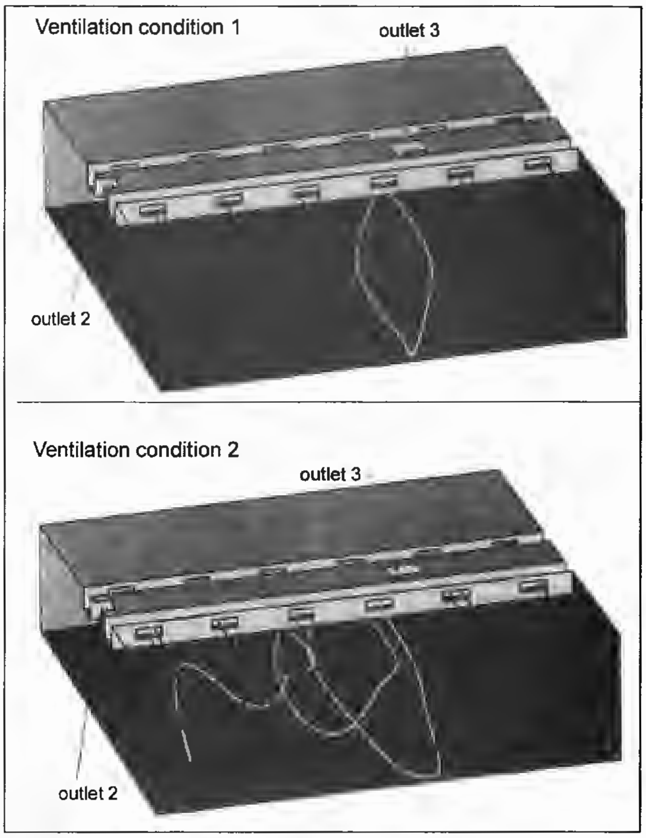

Fig. 6: Trajectories of massless particles for different ventilation conditions
condition 1: exhaust air flow ratio 1:1
condition 2: exhaust air flow ratio 1:4

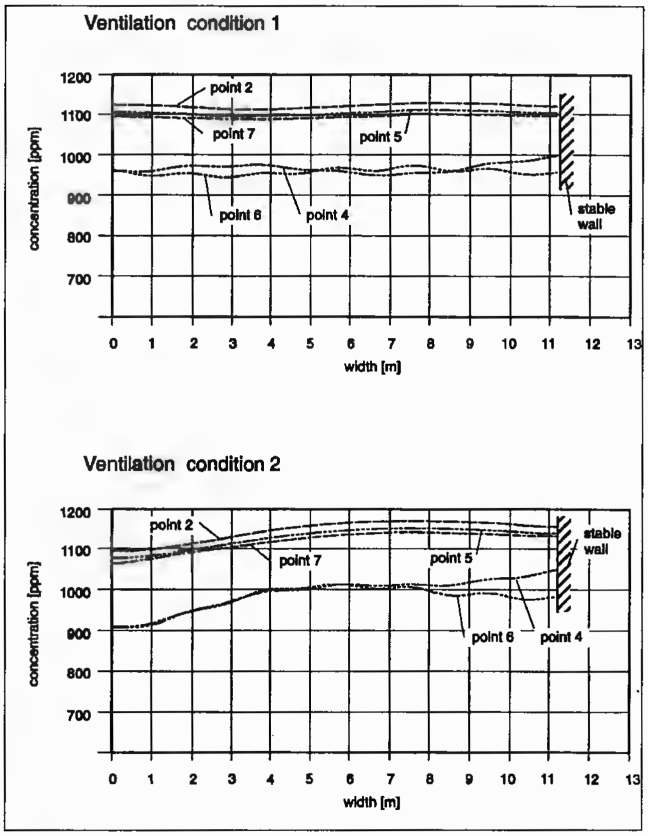

Fig. 7: Calculated concentration of carbon dioxide at sensor locations for different ventilation conditions
condition 1: exhaust air flow ratio 1:1
condition 2: exhaust air flow ratio 1:4

3.2 The naturally-ventilated Louisiana-type broiler house

As a further example of modelling three-dimensional flow and concentration fields inside a livestock building, studies were made of the same Louisiana-type broiler house (Figure 1b) as that studied experimentally [1]. This type of broiler house, which is common in Germany, provides ventilation openings by means of curtain walls down the long sides. They are hinged a distance above ground and open from the top down. It is very difficult to measure the volumetric flow rate in real systems. An important modelling parameter was the angle of incidence of the wind a. The cases $\alpha = 0°, 45°, 90°$, were studied (a = 0° means that the wind is normal to the house and passes directly through the side curtains, and $\alpha = 90°$ means that the wind is end on to the house).

The calculations assume a constant wind speed of n = 2.5 $m\ s^{-1}$. The resulting predicted concentration isolines shown in **Figures 8 - 10** ($\alpha = 90°, 0°, 45°$, respectively), are for a height of 1.5 m above the ground, i.e. the normal height of the human nose. The upper parts of Figures 8 - 10 show the flow field insside the house, again for an horizontal plane at a height of 1.5 m above ground. The main indication from Figures 8 - 10 is the very strong influence of wind direction.

Figure 8 shows the situation with the wind end on to the house. The air flow was forced around the upwind end wall and entered the house only after a certain distance, to leave it again near the downwind end wall.

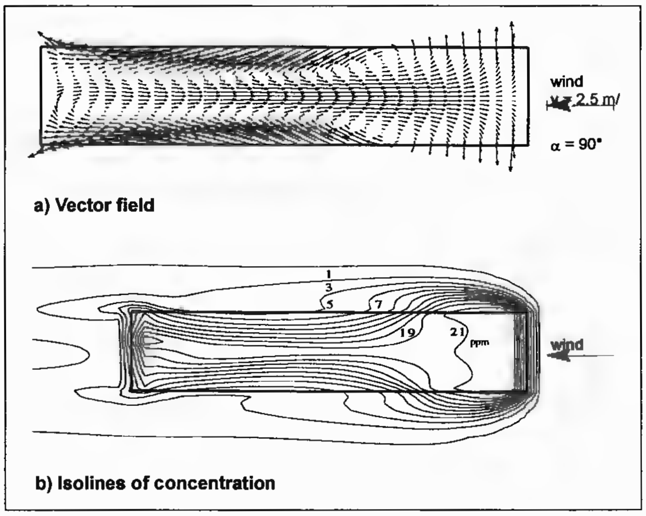

Fig. 8: Vector field and isolines of NH_3 concentration inside a Louisiana broiler house. Angle of incidence of the wind $\alpha = 90°$; horizontal cross section at a height of 1.5 m above ground

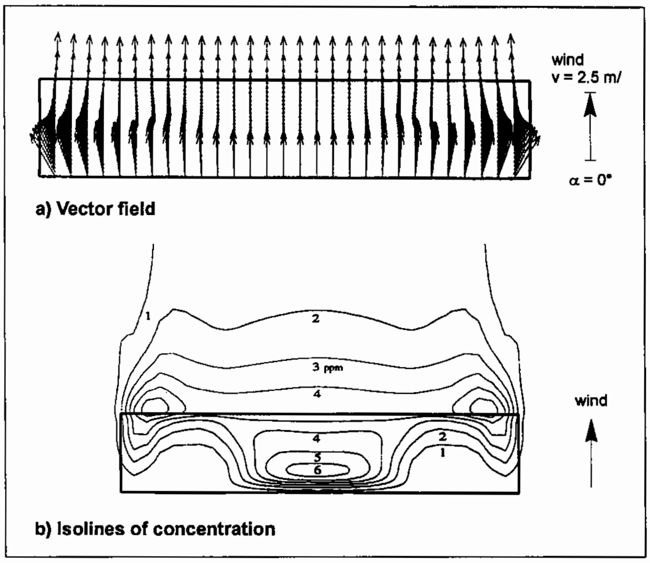

Fig. 9: Vector field and isolines of NH_3 concentration inside a Louisiana broiler house. Angle of incidence of the wind α = 0° horizontal cross section at a height of 1.5 m above ground

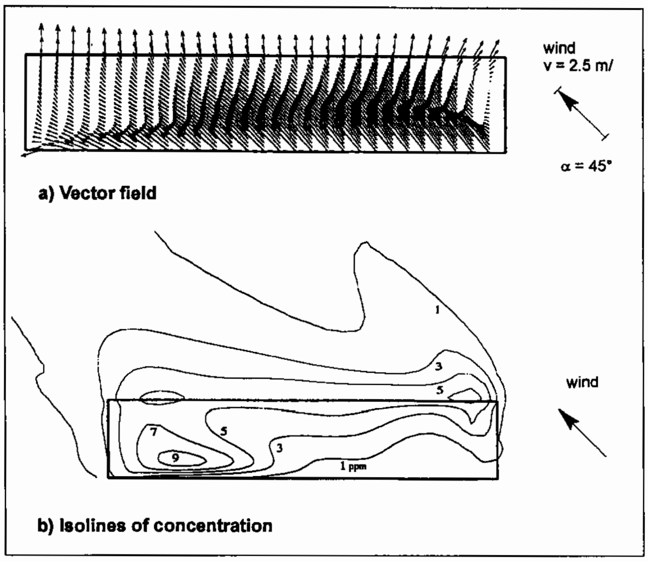

Fig. 10: Vector field and isolines of NH_3 concentration inside a Louisiana broiler house. Angle of incidence of the wind α = 45° degrees; horizontal cross section at a height of 1.5 m above ground

A reverse flow area was predicted in the centre of the building over the total length of the house. Figure 8b shows the resulting concentration field. Relative high concentration values are seen just downwind of the upwind end wall. Depending on the flow, the concentration decreased to much lower values near the side curtains. The concentration field is symmetric about the long axis of the house. The situation changes to orthogonal symmetry if the wind is broadside on (Figure 9). In the centre of the house, the wind passes straight through the house, with the highest velocity values near its end wall. The concentrations, as a result, were lowest there. The highest concentrations were predicted to be in the centre region of the house. For α = 45°, a very complex situation is predicted (Figure 10). An aerial pollutant will be carried with the air flow to the "downwind" part of the house. The maximum concentration arises in an area not far from the curtain in the "downwind" third of the house. In the "upwind" half of the house, the predicted concentration values were very low.

4 Results for the dispersion of pollutants around livestock buildings

As well as the problems of animal and human health and welfare from contamination inside a livestock building, effects on the external environment must also be considered. Therefore, this modelling study was extended to predict ammonia concentrations around the fattening piggery. This was realized by numerical solution of the Navier-Stokes equations. Calculations were carried out for typical ventilation conditions in summer and winter and for flow directions from the right and the left side, to study the influence of buildings asymmetry and the different fan outlets in the piggery. Beyond a certain distance from the piggery, no significant effect of the numer of fans in operation could be detected.

The piggery formed part of a larger building which has an assymmetrical roof (see **Figure 11**). If the wind was on to the steep side of the roof, concentration increases were predicted to occur further from the piggery than with wind on to the less steep side. But for either direction, concentration decreased significantly with distance, as Figure 11 shows.

While the above results show the situation in the immediate neighbourhood of the piggery for one direction and wind speed only, the following shows the result of a dispersion calculation for the whole year. **Figure 12** shows the results of dispersion calculations of ammonia concentration for a height of 1.5 m above ground level. The calculation is based on a Gaussian model for averaged concentrations. The Gaussian model is prescribed in Germany to predict

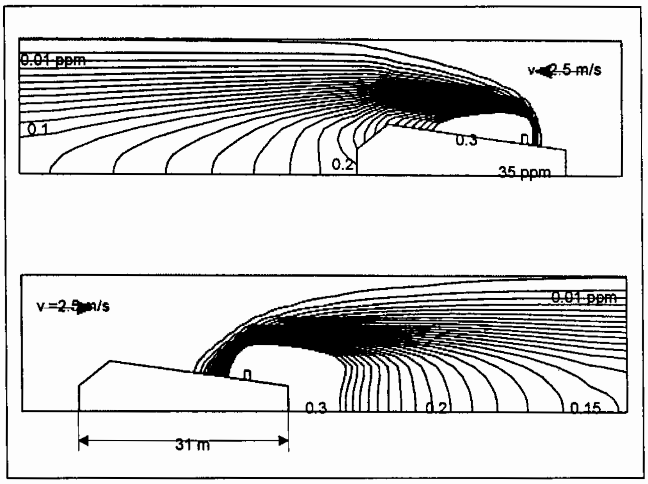

Fig. 11: Ammonia dispersion in ppm behind the fattening piggery for different incident wind directions

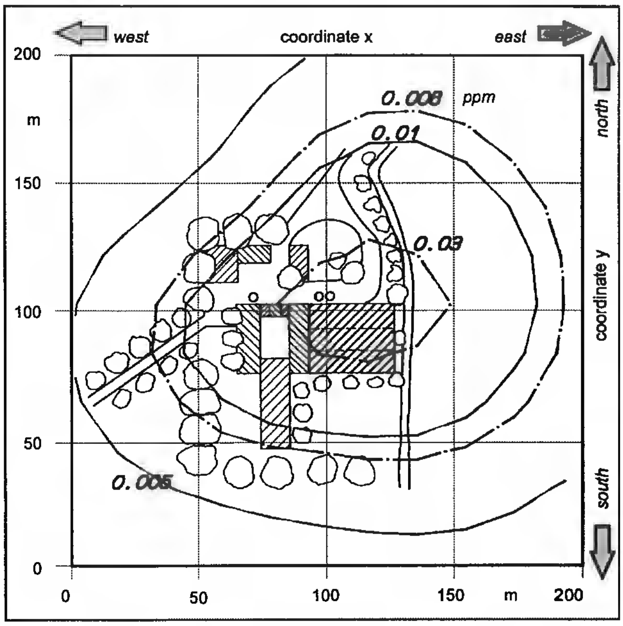

Fig. 12: Predictions of the dispersion in ppm of ammonia around the fattening piggery with an emitting concentration of 35 ppm assuming variable rates of emission over a year as given by S c h i r z [8] and K l u g [9]

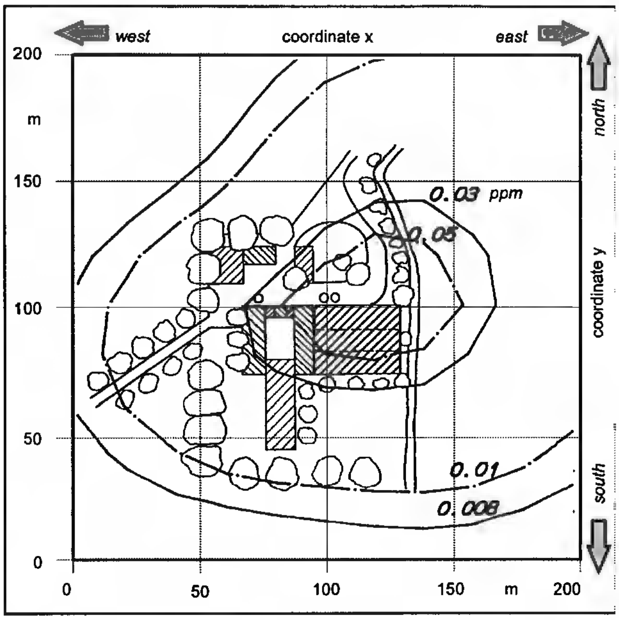

Fig. 13: Predictions of the dispersion in ppm of ammonia around the fattening piggery with an emitting concentration of 35 ppm assuming an emission rate typical of summer conditions

and describe aerial pollutant dispersion from point sources. The model describes the analytical solution of the so-called atmospheric diffusion equation. Obstacles in the wind are neglected. The meteorological parameters are the dispersion classes of K l u g [8]. In the present case, the meteorological statistic of Diepholz, a city in Northern Lower Saxony, not far from Vechta, was used. Figure 12 shows the predicted isoplethes of equal concentrations around the piggery. The concentration leaving the outlet fans was set at 35 ppm. The (maximum) volume flow in summer was about 38000 $m^3.h^{-1}$, (total from five outlets). The average concentration for the whole year was 0.008 ppm at a distance of 50 m to the south west and of 80 m to the north east.

Data about concentrations and exhaust air flow rates air provide information on emissions from stables with forced ventilation. These values, however, are subject to considerable fluctuations during the day and over the course of the year. In buildings with temperature control, the exhaust air flow rate be classified. It must be taken into consideration that building ventilation changes with the climatic conditions, which are characterized by factors such as the temperature and humidity of the surrounding air. A classification of the emissions can distinguish five classes or levels of emission [8, 9]. The different levels of emission occur for different fractions of the years. Maximum (summer) flow rate is only required during 10 % of the year. The average air flow rate occurs during 40 % of the year. If all classified flow rates are added, the flow relevant for the environment, amounts to 47 % of the maximum summer flow rate [8, 9]. The isoplethes in **Figure 13** show the dispersion for the whole year calculated from the summer air output. In comparison with Figure 12, the isoplethe for 0.008 ppm is 30 m from the piggery. The isoplethes in **Figure 14** show the dispersion for the whole year calculated from the winter output. In the immediate vicinity of the piggery, the Gaussian model predicts unrealistic concentrations [10].

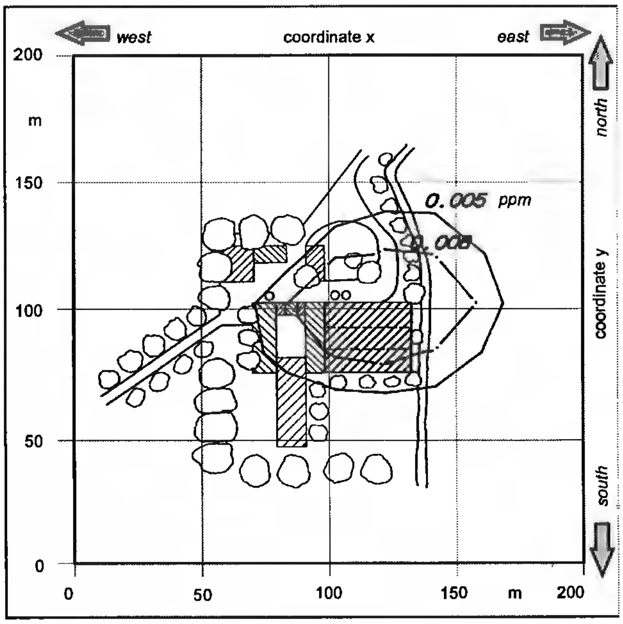

Fig. 14: Prediction of the dispersion in ppm of ammonia around the fattening piggery with an emitting concentration of 35 ppm assuming an emission rate typical of winter conditions

5 Discussion

Within animal houses, numerical methods for fluid flow simulation have been used. For predictions, which are accurate in detail, a 3-D calculation which is costly of computing time is necessary, but for long buildings with symmetrical air inlet and outlet arrangements, 2-D calculation gives adequate predictions. Around the outside of animal houses, simple analytic solutions are preferred, because of the variety of meteorological boundary conditions. The calculation of airflows and the distribution of contaminants for problems of practical interest is always characterized by complex geometries. Thus, for three-dimensional calculations, the assessment of the accuracy of the simulation is a complex and time consuming procedure.

In spite of computing limitations, two-dimensional numerical analysis was found to be an appropriate tool for supporting a reliable assessment of airflow when characterized by simple inlet conditions in complex geometries and symmetrical boundary conditions. In the case of simulating the air flow in a scale model, using a high resolution two-dimensional calculation, a failure properly to predict the inlet flow was identified. There was often a deviation between the computed air flow and the real air flow pattern within the ventilated chamber under consideration.

Flow simulation for complex ventilation arrangements, by discretizing the smallest unit of the piggery and applying symmetry conditions, led to realistic results when the exhaust air flow was equally distributed across all the outlet fans. In the case of a symmetrical exhaust air flow distribution, performing a simulation on one half of the piggery only still yielded a reasonable predicted flow pattern. Additional studies on complex geometries were prevented by limitations of the computing power available. The memory requirements for the calculations performed (a) on the fine grid in two dimensions within the scale model, (b) on a coarse three-dimensional mesh for the model chamber, (c) within a section of the piggery and (d) within a complete half of the piggery were in the ratio 1:4:6:17. Simulating additional contaminants and temperature would further increa-se the memory requirements. Thus, the application of CFD to complex problems is often limited by hardware considerations.

Using the commercial programme Flow D3 led to intersting results concerning the flow and concentration fields both inside the Louisiana broiler house and around the fattening piggery. The environment inside the naturally-ventilated house depended strongly on the angle of incidence of the wind, so that it seems to be difficult to extend the predictions to other situations from these results or to find representative sampling locations for measuring emissions. In the cases demonstrated, three typical regions in the house were observed, two near the respective end walls and one in the central region. The ihfluence of the gable walls was limited in distance, so that the present results may be transferable to longer Louisiana houses. However, emission rates cannot be estimated reliably from measurements at this location in the house. The central region of the house was suitable for comparative measurements of inside parameters, as were undertaken in the field studies [12].

Predicted ammonia concentration around the piggery at Vechta showed a concentration decreasing sharply with distance. Beyond a distance of one length of the house, the concentration decreased to values below 0.15 ppm for all situations calculated - summer, winter, flow from the right or the left side. Taking into account the real conditions of dispersion and using the Gaussian model, the relevant concentrations are one or two orders to magnitude lower. All these results predict a negligible influence of the piggery on the near environment e.g. a nearby woodland.

Conclusions

1. Calculating airflow and distribution of contaminants for problems of practical interest is always characterized by complex geometrical arrangement. Thus, for three dimensional calculations the assessment of the accuracy of the simulation is a complex and time consuming procedure and the application of Computational Fluid Dynamics to complex problems is often limited by hardware considerations. In contrast to investigations of the overall flow pattern within scale models, which often include simplifications of the original ventilation system, experimental and numerical effort increase for full scale studies of flow fields and distribution of contaminant.
2. In this paper, flow simulation of complex ventilation arrangement was facilitated by discretization of a domain representing the smallest unit of the ventilation system. Thus, in spite of limited hardware a reasonable distribution of velocity was calculated concerning the velocity decay within the incoming free jet. The comparison of measurement and calculation show a good agreement. As experienced in a previous study within a scale model [3] a failure in computing the inlet flow often results in a deviation of computed airflow and real flow pattern within the complete ventilated chamber being considered. Thus, for ventilation systems which satisfy a symmetry constraint, reducing the numerical model to a domain representing the smallest unit of the ventilation system should be a helpful tool to estimate velocity distributions.
3. The investigation of distribution of contaminant within the whole ventilated space not only increase the memory requirement teafold but also the experimental effort for model verification. Thus, the numerical model only yields a vague assessment of concentration field, when no accompanying detailed measurement is performed. However, the predicted results for carbon dioxide concentrations were in reasonable agreements with measurements. The influence of different ventilation conditions was also predicted reasonably well.

Thus, extending the procedure of examining con-taminant behaviour within livestock buildings by means of Computational Fluid Dynamics may reduce experimental equipment and manpower.

4. Numerical analysis is an appropriate tool to support a reliable assessment of airflow. However, detailed verification studies of numerical models have to be combined with simultaneous measurements of air velocity, concentration and turbulent quantities of high spatial resolutions to record a fully three-dimensional pattern. Those extensive experimental investigations should be the main work for detailed calibration of numerical models for room airflow ventilation.
5. Single measurement data should be interpretated with respect to the flow and concentration fields only. Measurement data represent single events in a manyfold of realizations. To understand the mass transfer of ammonia e. g. in an animal house the whole situation must be seen. At last, this will be done by simulation technique under real boundary conditions. This study describes the way of problem solving. The next step is the concretization of special problem solving solutions.

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Summary

Various numerical models were used to predict the movement and distribution of gaseous pollutants within livestock buildings. Furthermore, emissions from a force ventilated fattening piggery and a naturally-ventilated broiler house were determined.

There was reasonable agreement between predicted and measured flow fields and concentration fields when a two-dimensional model of a building's cross section was used. A three-dimensional model gave some improvement for asymmetric ventilation systems, at the expense of more computing time. Concentrations of aerial pollutants in a naturally-ventilated broiler house showed a strong dependency on the wind direction.

Atmospheric transport and turbulent dispersion of aerial pollutants from the fattening piggery ensured a rapid decrease of the concentration of pollutants with distance from the building.

Numerische Modellierung der Emissionen luftgetragener Stoffe in und aus Tierställen

Verschiedene numerische Modelle werden herangezogen, um die Bewegung und Verteilung von Luftbeimengungen im Stall vorherzusagen. Untersucht werden Emissionen von zwangsbelüfteten und freigelüfteten Ställen.

Bei den langgezogenen zwangsbelüfteten Ställen erweisen sich zweidimensionale Strömungsmodelle im Stallquerschnitt bei symmetrischen Zu- und Abluftbedingungen als angemessen. Bei asymmetrischen Verhältnissen sind dreidimensionale Strömungsmodelle erforderlich. Das gilt erst recht für die windrichtungsabhängigen freigelüfteten Ställe.

Der atmosphärische Transport und die turbulente Diffusion bewirken einen relativen schnellen Abbau der Konzentrationen von Luftbeimengungen bei der Ausbreitung außerhalb des Stalles.

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