CFD Analysis to Predict Close Range Spreading of Ventilation Air from Livestock Buildings

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ABSTRACT

Odour annoyance from livestock production is an increasing problem in many countries, and efforts to reduce the odour inconvenience are necessary to maintain or establish good relations between animal producers and their neighbours. Ventilation exhaust is usually the most significant odour source from livestock production and full scale tracer gas measurements shows that the location and design of exhaust have a significant influence on the spreading and distribution of exhausted air in the close surroundings. The paper describes a CFD (Computational Fluid Dynamics) model to investigate the possibilities to reduce odour concentrations by optimising the location and design of exhausts.
The CFD model was validated against full scale tracer gas measurements around a commercial growing-finishing pig building and subsequently the model was used to investigate how six different exhaust configurations is expected to influences the concentration of exhausted air at neighbours located at two different distances from a production unit.
Comparison with the full scale tracer gas measurements indicated that the used CFD-method is a suitable technique to predict the spreading of exhausted air 50 to 150 m form a livestock building. The investigation of the six different exhaust configuration demonstrated that a change in the location or layout of exhausts can have a significant influence on the exposure of exhausted air at down wind located neighbours.

Keywords: CFD (Computational Fluid Dynamics), Numerical simulation, Distribution of exhausted air, Exhaust configuration, Mechanical ventilation, Livestock buildings, Odour.

INTRODUCTION

Odour annoyance from livestock production is an increasing problem in many countries, and efforts to reduce the odour inconvenience are necessary to maintain or establish good relations between animal producers and their neighbours. The most important odour annoyance from livestock production is usually caused by of ventilation exhaust (Kai et al., 2003; Defoer and Van Langenhove, 2003) and full scale tracer gas measurements (Ellerman and Løfstrøm, 2002) shows that the layout and location of exhausts have significant influence on the down wind spreading and distribution of exhausted air up to 150 m from a pig production facility. Consequently, possibilities to anticipate the connection between the exhaust layout and spreading of exhausted air in the neighbourhood can be utilized in planning of new or improvement of existing production facilities in order to reduce the odour annoyances.

Prediction of odour annoyance from livestock facilities have in several cases been based on dispersion models including the Gaussian plumes theory (Pasquill and Smith, 1983) see e.g. Smith (1993) and Chen et al. (1998). This type of dispersion model require only limited information of the local geometry around the emission source, which makes them relative easy to use. But ventilation exhausts from livestock buildings are typically located close to building surfaces where the local geometry have a crucial influence on the airflow, and consequently, the poor ability to include the geometry limits the prediction accuracy especially close to buildings or other obstacles close to the production facility.

Computational Fluid Dynamics (CFD) is a prediction tool that requires a detailed geometric model of the investigated air space and potentially it is suitable to predict dispersion phenomena where local geometry is significant for the airflow. In connection with livestock production the potential of CFD method have been demonstrated by comparison with test room measurement of isothermal airflow (e.g. Harral and Boon, 1997; Bjerg et al., 1999 and 2002), none isothermal airflow (e.g. Bjerg et al., 2000) and dust distribution (e.g. Reynold, 1997). But the literature does not seem to contain earlier works on the use of CFD in relation to predicting odour dispersion around livestock buildings.

The aim of this study is to investigate the ability of a CFD model to predict the dispersion of livestock ventilation exhausts and to investigate possibilities to reduce the odour concentrations in the surroundings by optimizing the location and layout of exhausts.

MATERIAL AND METHODS

The CFD-model is validated against full scale tracer gas measurements (Ellerman and Løfstrøm, 2002) around a commercial growing-finishing pig building and subsequently the model is used to investigate how different exhaust configurations is expected to influence the concentration of exhaust air and thus the concentration of odorants at different distances from a production unit.

Dataset for validation of CFD-model

Full scale tracer gas (SF_6) measurements (Ellerman and Løfstrøm, 2002) were carried out around a 61 m long, 23 m wide and 5.7 m high grower-finisher pig building located in Roager in the southern part of Jutland, Denmark. The orientation of the building was 100 degree relative to the north – south direction. The building was equipped with 10 exhausts equally distributed 0.65 cm above the ridge. The dataset used recorded the 17th of June 1999. Due to high ambient temperature (18-20 °C), the ventilation rate was, assumed to be equal to the ventilation capacity of 13.000 m^3/h per exhaust. Equally distributed above the opening area (0.71 m^2) the exhausted air corresponded to a mean air velocity of 5.1 m/s.

Tracer gas was applied together with smoke (for visualization – see Mikkelsen and Jørgensen, 2002) through a 125 mm flexible tube system (artificial exhausts) and released with a vertical velocity of 20-25 m/s. The used data includes three experiments with different locations of tracer gas release. The tracer gas (and smoke) was added to one or four ordinary exhausts

(0.65 m above roof ridge) or 6.05 m above roof ridge, see figure 1 and table 1. Wind direction, wind speed and turbulent kinetic energy were measured 7 m above ground level.

Table 1. Overview over experiments used for validation.

Exp.	Time	Type of release	Wind speed, m/s	Turbulence energy, m^2/s^2	Wind direction*, degree
1	12.08-12.38	in 4 existing exhaust	3.7	0.43	334±3
2	12.47-13.17	one 6 m above roof	3.9	0.43	251±4
3	14.03-14.33	in 1 existing exhaust	4.5	0.70	239±7

*mean and standard deviation

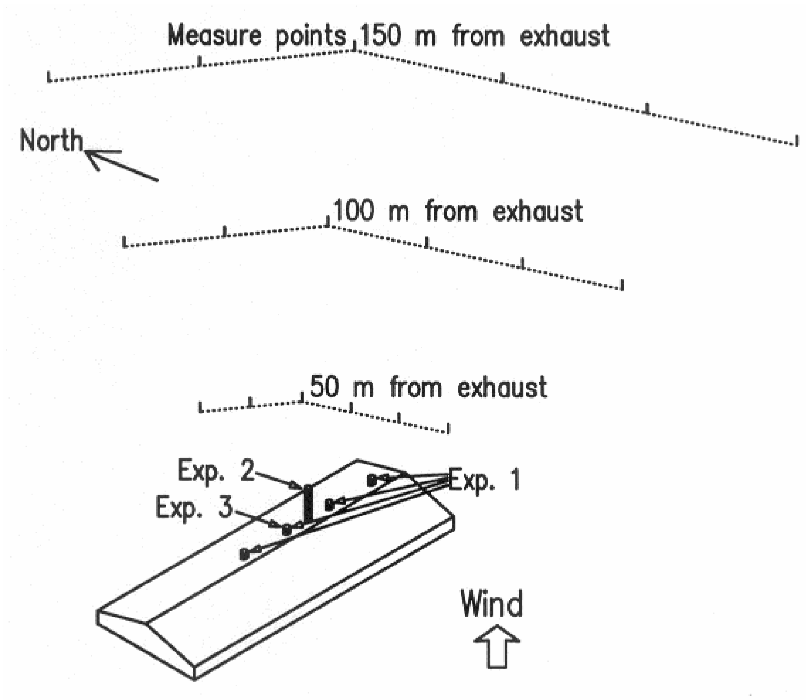

Figure 1. Location of measure points and tracer gas release in experiment 1, 2 and 3.

Tracer gas concentration was measured in the down wind direction at 18 points located 1.8 m above ground level in chains 50, 100, 150 m from exhausts, see figure 1. The spacing between measuring points in each chain were 10 degree. At each measuring point a sampler was located for collecting a constant air flow in a PTFE (poly-tetra-fluor-ethylene) plastic bag for later determination of tracer gas concentration. The samplers were radio controlled to synchronize the beginning and end of air collection (Ellerman and Løfstrøm, 2002).

CFD

Air flow and dilution of tracer gas were predicted by the commercial CFD code Fluent 5 (Fluent Inc). The K-ε turbulence model (Launder and Spalding 1974) and the first order upwind descretization scheme (see Anonymous 1998) were generally used in simulation in this work. In a few additional simulations the Spalart-Allmaras Turbulence model, the Reynolds Stress turbulence model and the second order upwind descretization scheme (see Anonymous 1998) were used. A 600 m long, 600 m wide and 200 m high domain was used and the buildings were centred at ground level of the domain. In order to reduced the complexity of the geometrical models the exhausts were modelled as rectangular tubes. The exhausts and the domain delimitation in the up wind side were modelled as inlet velocity boundaries. The domain delimitation in the down wind side was modelled as out flow boundaries. The upper delimitation of the domain was modelled as a symmetrical boundary. Wall functions were applied at ground and building surfaces.

Boundary condition for exhaust velocity

Plume elevation caused by the vertical velocity of the exhausts is expected to be crucial for the prediction of dilution close to ground level. Consequently, a CFD model was used to determine which vertical velocity should be used in the assumed rectangular opening in order to obtain the same plume elevation as in a more detailed model, including circular opening, flow in diffuser (expansion of exhaust tube diameter from 0.6 to 0.95 m) and finer grid resolution. These simulations showed that the air velocity should be about 4.5 m/s in the assumed rectangular opening in order to obtain the same plume elevation as in the detailed model with an airflow of 13,000 m^3/h. In experiment 1 and 3 the artificial exhausts was located in exiting exhausts and the simulations showed that the exhaust velocity should be 5.1 m/s in the assumed rectangular opening in these cases. In experiment 2 an artificial exhaust was used alone and the simulations showed that it would require a exhaust velocity of 3.0 m/s in the assumed rectangular opening.

Boundary condition for wind speed and turbulence

Vertical wind velocity profiles where calculated from equations (1) and (2), (Richards 1993).

$$U = \frac{u_*}{K} \ln\left(\frac{z + z_0}{z_0}\right) \quad (1)$$

where U is streamwise velocity, m/s,
u_* friction velocity, m/s (calculated from equation (2)),
K von Karman´s constant (≈0.4),
z height above ground, m and
z_0 surface roughness length.

$$u_* = \frac{K\,U_h}{\ln\left(\frac{h + z_0}{z_0}\right)} \quad (2)$$

where U_h is measured velocity, m/s and
h height of measured velocity.

Richards (1993) measured vertical wind profiles at Silsoe (UK) and determined the surface roughness length to 0.01 m. Due to assumed similarity in landscape the same value was used in this study. The dissipation of kinetic energy in the wind profiles was calculated as recommended by Richards (1993).

Measured wind speed, turbulence energy and wind direction in 7 m height, mentioned in table 1, were used to validate the simulation method. From table 1 and figure 1 it appears that the wind direction were not aligned with the building dimensions in any of the 3 experiments. To establish equal conditions in the two sets of simulations the assumed wind direction was neither aligned with building dimensions in the succeeding simulation of the relation between exhaust configuration and concentration of exhaust air at neighbours. Wind speeds of 2 and 5 m/s, respectively, in 10 m height were assumed in the later simulations.

Geometry and grid

Two geometric models were used. Model A containing 111,776 cells was used for comparison with the tracer gas measurements. Model B containing 209,104 cells was used for investigation of six different exhaust configurations from a 80 m long, 20 m wide and 7 m high livestock production building, located 50 m from a residential area (figure 2). The air velocity in the normal exhausts mentioned in figure 2 was 4.5 m/s and the total exhausted air volume were 52,000 m^3/h in all six exhaust configurations. The geometry of the four normal exhausts was equal to the exhausts used in model A. The succeeding exhausts configurations listed in figure 2 were designed to investigate the effect of increased release height, of increased release velocity, and of joining the exhaust and moving the release to the end of building opposite to the residential area.

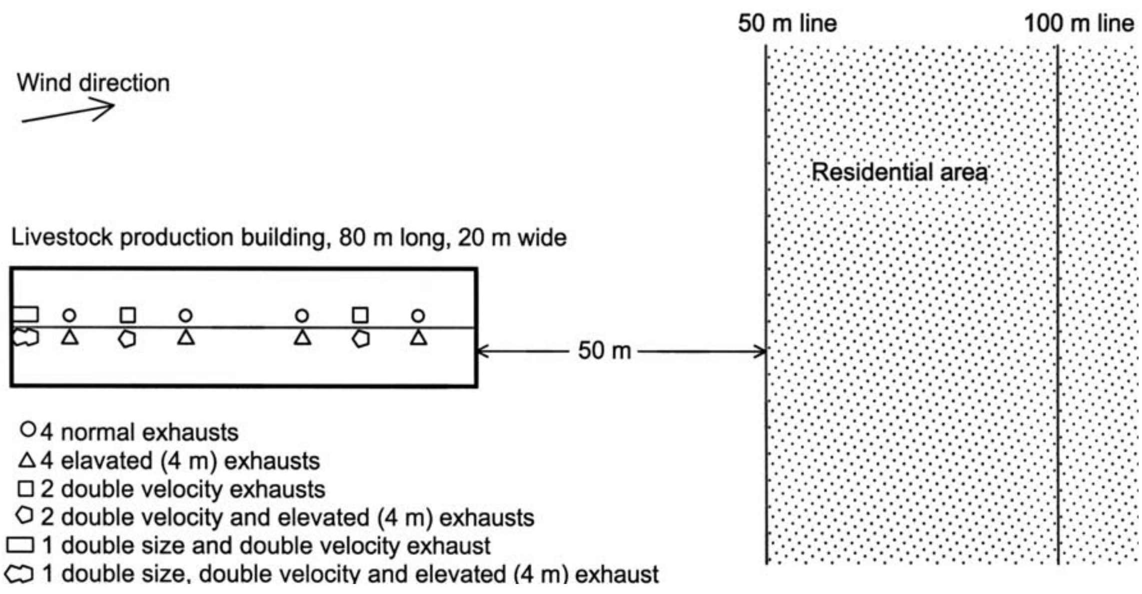

Figure 2. Overview over investigated exhaust configuratitions (model B).

Both models were build of hexahedral cells and the grid density where increased around the building and in the downwind side of the building. The choice of cell type was motivated by requirement of efficient utilization of computer capacity and control of cell sizes close to surfaces. The grid distribution on building surfaces and the surrounding ground surface is shown in figure 3.

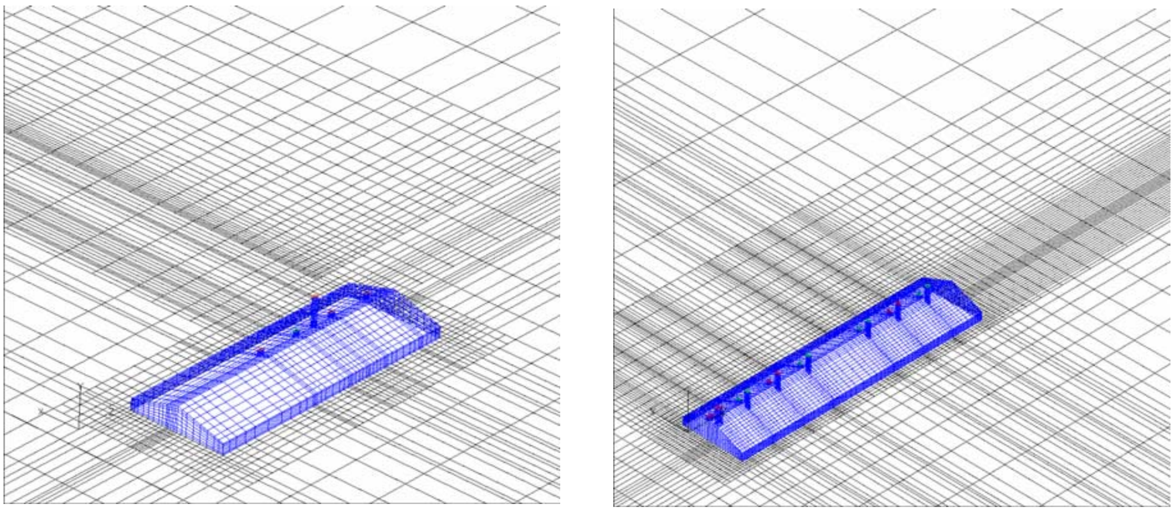

Figure 3. Grid distribution on building surface and surrounding ground surface. Model A to the left and model B to the right.

An additional grid was used to indicate possible grid dependency. This grid consisted of 671,963 cells and was derived from model A by refining all cells up to 20 meter from ground level.

RESULTS AND DISCUSSION

Validation of CFD model

Measured and simulated SF_6 concentrations in the three experiments are compared in figure 4. With four normal exhausts the figure shows good agreement between simulated and measured values at most measuring points, but the highest simulated values were generally higher than the corresponding measured values. With one elevated exhaust the figure shows that there was very good agreement between measured and simulated values. With one normal exhaust the highest simulated concentrations seems to be about 10 degree displaced compared with the measured values and the highest simulated values were 34 % higher than measured at 50 m from the exhaust. 100 and 150 m from the exhaust the difference between the largest simulated and measured values were 22 and 13 %, respectively. Despite these discrepancies it clearly appears from figure 4 that the CFD-model was able to capture the differences between the level of the measured values in the three experiments which indicates that the used simulation methods are suitable in predicting the effects of different exhaust configurations.

The additional simulations showed that both the second order upwind descretization scheme and the refined grid caused decreased diffusion of exhausted air and, consequently increased concentration in the central part of the plume. The grids and wind directions assumed in this study imply diagonal airflow in cells which can cause numerical diffusion and consequently uncertainties in numerical simulations (See e.g. Anonymous 1998). Use of finer grid and second order descretization schemes is recommended to reduce numerical diffusion (Anonymous 1998). But in this study the use of a relatively coarse grid and the first order descretization scheme did not indicate that the diffusion of exhausted air was larger in simulations than in the measurements.

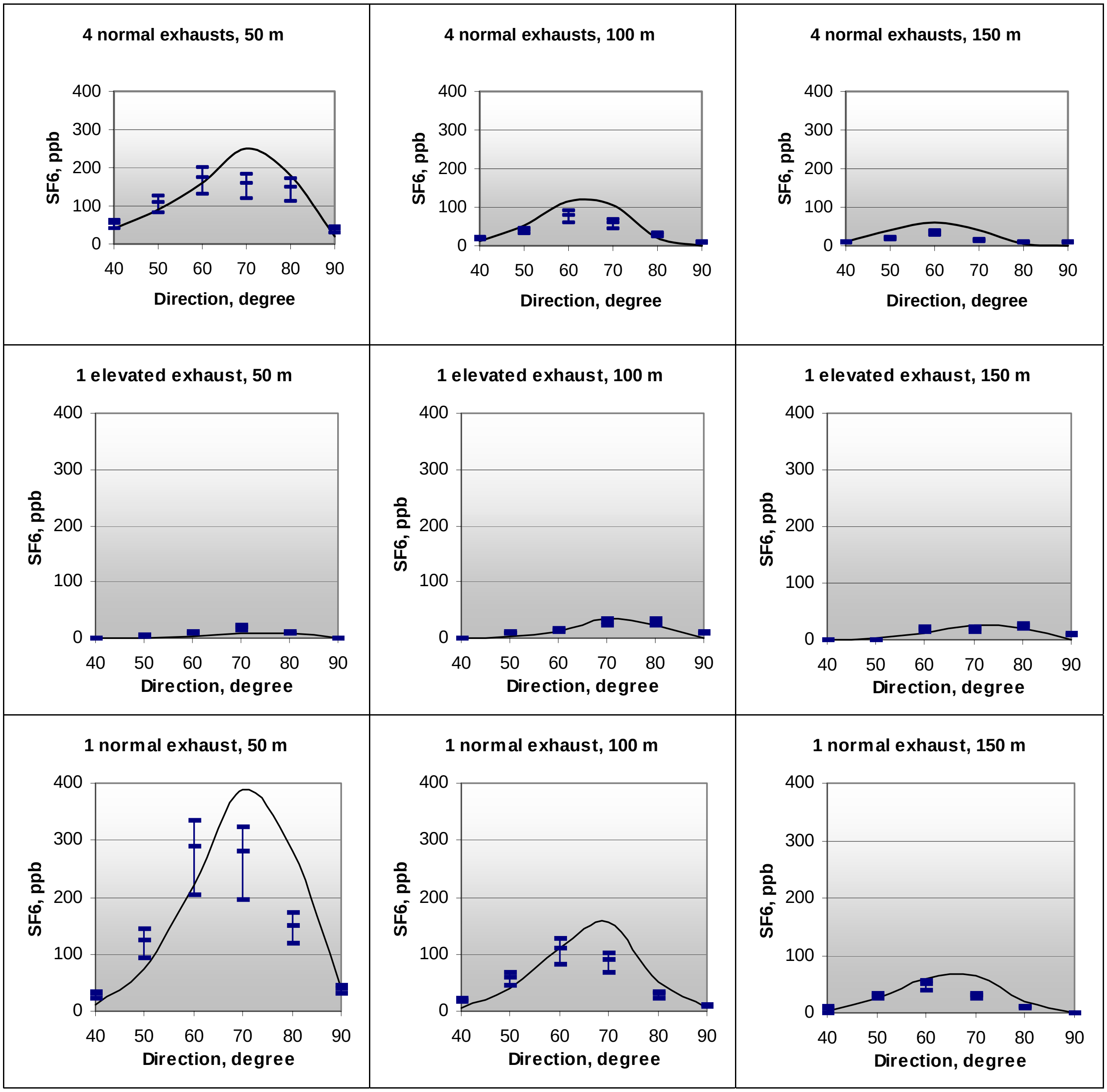

Figure 4. Measured and simulated SF_6 concentration 1.8 m above ground level at different distance and direction from building centre (Model A). Experiment 1 above, experiment 2 in the middle and experiment 3 below. First column 50 m from source, second column 100 m from source and third column 150 m from source. Solid lines shows CFD-results and markers shows measured mean values and estimated uncertainties (see Ellerman and Løfstrøm, 2002) on measured values.

Changing the turbulence model from K-ε to the more simple Spalart-Allmaras model increased simulated concentration of exhausted air in the central part of the plume with about 40 %. Opposite to that a change from K-ε to the more complicated Reynolds stress model had only insignificant influence on the concentration in the plume.

Effect of exhaust configuration

Figure 5 shows simulated concentrations of exhausted air 2 m above ground level along the 50 m line (see figure 2) using the six different exhaust configurations at air velocity of 5 m/s. From the figure it appears that the exhaust configuration has significant influence on the level of exhausted air 50 meters from the building.

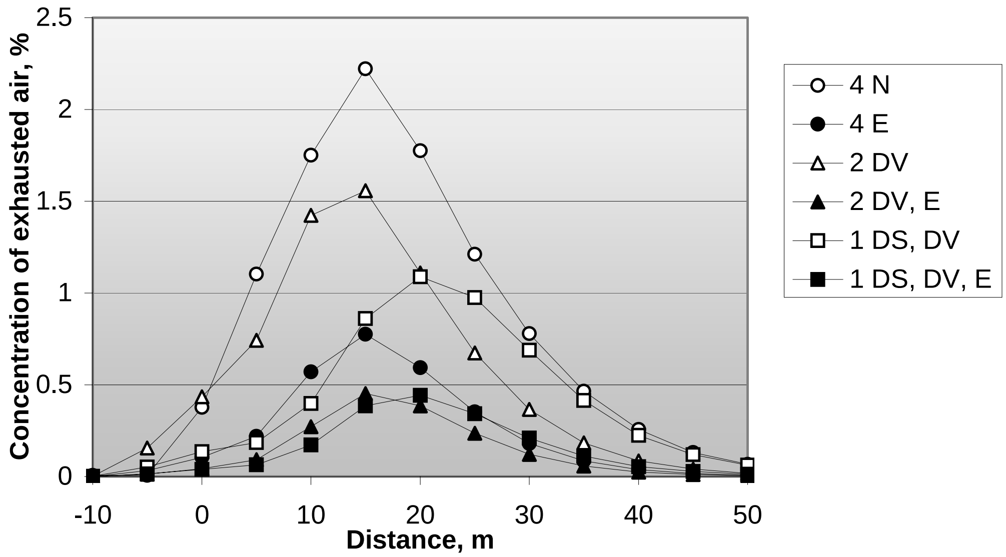

Figure 5. Simulated concentrations of exhausted air 2 m above ground level along the 50 m line (Model B, see figure 2) using six different exhaust configurations at air velocity of 5 m/s (N: normal exhaust, E: elevated exhaust, DV: double velocity, DS: double size).

Figure 6 shows the highest simulated concentrations of exhausted air 2 m above ground level at the 50 m and the 100 m line (see figure 2) using the six different exhaust configurations at air velocity of 5 and 2 m/s. With four normal exhausts the concentration of exhausted air were up to about 3 % 50 m from the building and up to about 1.5 % 100 m from the building. The figure show surprisingly small influence of wind speed 2 m above ground level. The reason seams to be that a larger part of the exhausted air is transported to higher air layers at low wind speed. The results also show that the elevation of the exhaust with 4 m reduced the highest simulated exhaust concentration 2 m above ground level by 60-76 % at the 50 m line and 47-63 % at the 100 m line. Doubling of exhaust air speed reduced the concentrations of exhausted air at the 50 m line by 30-42 % at wind speed of 5 m/s and by 59-71 % at wind speed of 2 m/s.

Moving the two normal height double velocity release to one double size exhaust located at the opposite end of the building reduced the highest concentration at the monitoring lines with about 35 %. At elevated release height the influence of moving the release to the opposite end of the building was les significant.

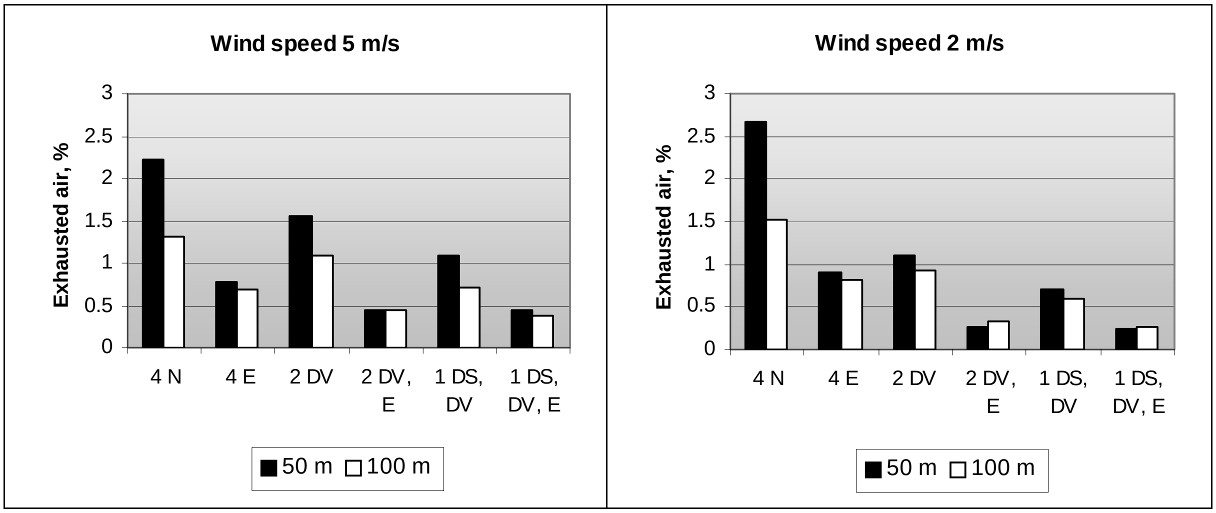

Figure 6. Highest simulated concentrations of exhausted air 2 m above ground level at the 50 m and the 100 m line (see figure 2) using six different exhaust configurations at air velocity of 5 and 2 m/s, respectively (Model B).

Figure 7 illustrates the simulated spreading of exhausted air from four normal exhausts and from one double velocity, double size and elevated exhaust at an air speed of 5 m/s. It appears that air from the elevated exhaust becomes faster diluted, and the highest concentration of exhausted air is located in larger distance from ground level.

CONCLUSSIONS:

A CFD model was developed to predict the dispersion of exhausted air from mechanical ventilated livestock production facilities. The model was validated against tracer gas measurement (SF_6) around a full scale commercial pig production building. The prediction results were in good agreement with the measurements and the model was able to distinguish between different exhaust configurations.

Furthermore, the simulation method was used to investigate how different exhaust configuration from a mechanical ventilated animal productions building can be expected to influence the concentration of exhausted air 2 m above ground level 50-100 m from the building. Under the conditions used, the investigation showed that:

- Using four normal exhausts the concentration of exhausted air were up to about 3 % 50 m from the building and up to about 1.5 % 100 m from the building.
- Elevation of the exhausts by 4 m reduced the highest simulated concentration by 60-76 % (50 m from the building).
- Doubling of vertical exhausts air speed reduced the concentrations of exhausted air at the 50 m line by 30-42 % at wind speed of 5 m/s and by 59-71 % at wind speed of 2 m/s.

Overall the investigation confirmed that a CFD model can be suitable to estimate the spreading of exhausted air close to livestock production facilities and that a change in the location or layout of exhausts can have a significant influence on the exposure of exhausted air at down wind located neighbours.

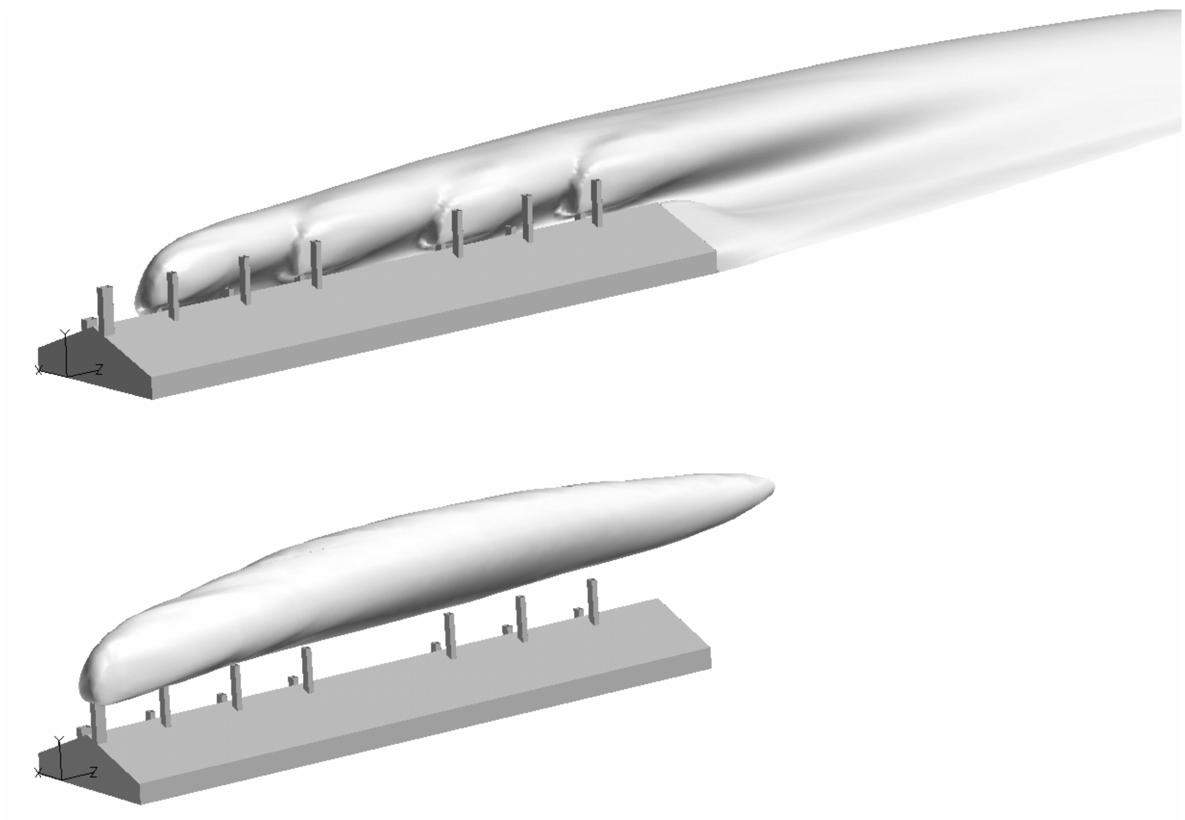

Figure 7. Spreading of exhausted air from 4 normal exhausts (above) and 1 double velocity, double size, elevated exhaust (below) at wind speed of 5 m/s (Model B). The clouds show the volume where the exhausted air is diluted less than 100 times.

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