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Measuring and simulation of the distribution of ammonia in animal houses

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Session C – 7

MEASURING AND SIMULATION OF THE DISTRIBUTION OF AMMONIA IN ANIMAL HOUSES

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The situation of ammonia emissions from animal houses

Atmospheric ammonia is discussed as a serious environmental issue. The major contribution to the total ammonia emission is given by livestock wastes. Therefore much effort is spent to measure ammonia emission from livestock wastes. Though there is a lack of knowledge in the quantitative description of ammonia emission far-reaching prognoses are made. On principle the demand for minimizing the ammonia emission must be supported. One concept of technical realization is the assignment of industrial filter plants; but up to this day the availability of biofilters in animal production is unacceptable and the investigation sums are very high (1). Our concept consists in making use of the flow pattern within animal houses. The rate of ventilation (2) and the location of ventilation devices (3) influence ammonia concentration.

Feed efficiency and rate of gain of the animals are the main reasons for confinement systems. Manure from animals is stored in pits under the slatted floor. Biological degradation of the manure releases gases to the air within the animal houses. These gaseous contaminants are ammonia, methane, hydrogen sulphide and carbon dioxide. Another mass transfer into the air is given by water vapour. Carbon dioxide and water vapour are contributed by animal respiration too. Beyond this water vapour is supplied by evaporation from wet floor areas and through the skin of the animals. Besides the input of mass there is an input of energy in form of heat by the animals.

Heat and moisture are controlled by mechanical ventilating systems, currently. The controlling concept is based on physiological data for animal welfare. By the momentum input the air is moved. The contaminants are transported through the space and ejected by ventilation from the confinement system into the environment.

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The airspace is not perfectly mixed. The inhomogenity of distribution of contaminants can be used to reduce the output of ammonia from animal houses without endangering the animals.

Physiological responses of the animals to contaminants - here pig responses to ammonia especially - are not clear. Drummond et al. (4) find that 50 p.p.m. of NH_3 slow growth and cause mild respiratory disorders. Scott et al. (5) say that ammonia concentrations below 75 p.p.m. have no significant influence to the growth (4) of finishing pigs. In general ammonia concentrations can be measured within the range of 5 to 30 p.p.m. in pig houses. So it is not presuming to consider the ammonia production as a problem of emission to the environment only. In this paper we present a study about the possibilities to cause a reduction of ammonia emission from livestock buildings by altering the flow pattern. This can be realized by suction channels with different clack closures as inlet cells.

Mathematical formulation of the problem

The physical model we make use of in this study is shown in Figure 1. A rectangular coordinate system is considered with the x-axis oriented parallel to the ground beginning in the left corner point of the cavity. The z-axis is directed vertically upward. The height H of the cavity is 2.75 m, the length L is 12 m. The floor area is characterized by two boxes (pen) for the animals each confined by two obstacles. At the bottom of these boxes the sources of ammonia are placed. The height of the obstacles is 35 % of the space height.

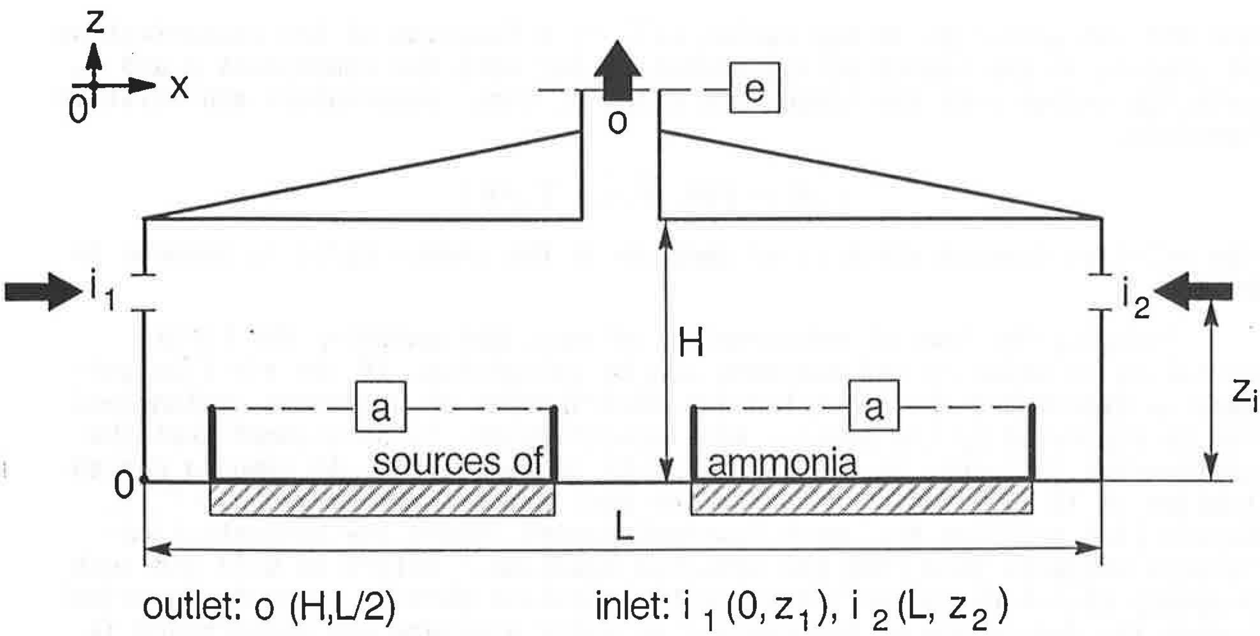

Fig. 1. Simplified vertical cross-section of a pig house and boundaries.

The mass transfer from the source cells into the air is assumed to be proportional to the air velocity (6). The mass transfer coefficient k with the unit 1/s is given by (7)

$$k = 1769 \ V^{0.8} \ T^{-1.4}$$

V represents the air velocity in m/s und T the temperature in K. For T = 293 K the mass transfer coeffient becomes $k = 0.6225 \ V^{0.8}$. This relationship must be verified for the conditions in animal houses (8).

With restriction to the x-z-plane in Figure 1 the flow problem is reduced to a problem in two space dimensions. A symmetrical arrangement is given. By ventilation fresh air is sucked through inlet cells into the livestock building and air loaded with contaminants is ejected into the environment (e). The position of the outlet cells "o" lies in the middle of the ceiling, o(H,L/2). The position of the inlet cells "i" varies. We study different positions of inlet cells in the ceiling i(x, H) and different positions in the side-wall i(0 or L,z). Chaturvedi et al. (9) present the velocity field v and concentration contours of carbon dioxide distribution for three different intake and exhaust vent geometries.

The mass of ammonia emitted into the environment during the interval $t_2 - t_1$ is given by

$$m_0 = \int_{t_1}^{t_2} c_0(t) \ \dot{V}_0(t) dt$$

The ventilation stream is determined by the physiological data of the animals

$$\dot{V}_0(t) = f(animal \ \ physiological \ \ data)$$

and the concentration in the outlet cell is a function of the concentration of ammonia in the source cells, radius vector with the components x and z, velocity vector with the components u and w, time, temperature and relative humidity,

$$c_0(t) = f(c_s, \vec{r}, \vec{v}, t, T, rh)$$

The relative concentration c_s of ammonia in the source cells is assumed to be 100.

Applying the laws of conservation of mass and momentum the field variables of velocity and pressure can be calculated. If the air flow pattern is determined the concentration distribution of a gaseous contaminant can be expressed by the partial mass conservation. It is assumed that the contaminant influence on the air velocity is negligible. An ammonia concentration of 10 mg/m^3 will influence the mass average velocity by 10^{-5}. T. Kusuda (10) critizes that most "current papers ignore the concentration-related buoyancy term from the momentum equation." Before we will use such buoyancy philosophy we will give up the constant density concept: in animal houses the dependence of the density on water pressure and temperature is of the same order of magnitude (11). In this study the influences of temperature and humidity to the density are neglected because of the dominant flow pattern: the flow pattern influences are of first order - so far the ventilation is in action - and the temperature and water vapour influences are of second order.

In order to consider turbulence influence the velocity and the concentration is splitted into time-smoothed and fluctuation (apostrophe) terms. This leads to a time-smoothed convection-diffusion equation where the turbulent mass flux must be determined. Because of the introduced unknown variables a closure problem arises. By analogy with the description of molecular diffusion the mass transfer by turbulent fluctuation is postulated as (12)

$$\overline{u'c'} = -D_x \frac{\partial c}{\partial x}, \qquad \overline{w'c'} = -D_z \frac{\partial c}{\partial z}$$

We need information about the turbulent diffusion coefficients D_x and D_z. Meanwhile we are able to measure ammonia as a function of time und space by means of chemical sensors. The determination of the coefficients is the next problem.

Sensoring measurement technique for ammonia

Ammonia in animal houses arises from the decay of albuminous organic material in manure by biological activity. It can not be a leading substance for malodors, but it is easiest to measure in regard to the odour components.

For simulations information about the mass transfer of ammonia from aqueous solutions is very important. Ammonia is very soluble in aqueous solutions and the rate of volatile ammonia is strongly dependent on pH and temperature of the solution.

Ammonia concentration in air is most frequently measured with test-tubes. In these the colour of a solid reagent changes if in contact with the active gas. Test-tubes are not useful for continous measurements.

Several physical-chemical measuring methods are available for detection of gaseous ammonia. The change of intensity of light due to the amount of active gas can be determined or, when the active gas is removed from air by a chemical scrubber, the change in conductivity of the aqueous solution can be determined. The last method was used for calibration of the employed five field effect transistors. As far as we know it is the first time to measure ammonia concentration in animal houses with field effect transistors.

The sensors utilize electric effects arising from the catalytic adsorption of gas molecules on the surface of thin active metal gates (palladium) on top of a semiconductor, which then dissociate and diffuse rapidly through the metal film and form a dipole layer at the metal-silicon dioxide interface. The dipole layer causes a negative change in the threshold voltage of the so-called MOSFET transistor (Metal-Oxide-Semiconductor-Field Effect Transistor). This change is a measure of the amount of the active gas in the ambient air.

The sensitivity and selectivity for the active gas molecules must be very high. If for example the voltage is influenced by several air contaminants $C_{1,2,3}$ and temperature T we can write

$$dU = \frac{\partial U}{\partial C_1}|_{C_{2,3,\dots T}} dC_1 + \frac{\partial U}{\partial C_2}|_{C_{1,3,\dots T}} dC_2 + \dots + \frac{\partial U}{\partial T}|_{C_{1,2,\dots}} dT$$

High selectivity for ammonia is given if the partial derivation to C_1 is dominant. Due to the design, the used ammonia sensor is insensitive to ambient temperature variations. The sensor is a progress of the already thoroughly investigated hydrogen sensitive Palladium-MOS capacitor and the high sensitivity for ammonia gas is obtained by evaporation of a thin film of platin on the Pd gate (13). No interference from moisture at 20 °C is observed. A small response from hydrogen and also from hydrogen sulphide may be obtained. In animal houses normally the amount of hydrogen sulphide is much smaller than of ammonia. Therefore the small response from hydrogen sulphide is negligible.

High selectivity for ammonia then gives

$$dU = \frac{\partial U}{\partial C} dC$$

and integrated

$$C = C_0 \left(\frac{U_0 - U}{K} \right)^m$$

where C_0 and U_0 are reference values for concentration and voltage respectively. K and m are the so-called sensor parameters determined by calibration. The relation between voltage and concentration is an exponential function.

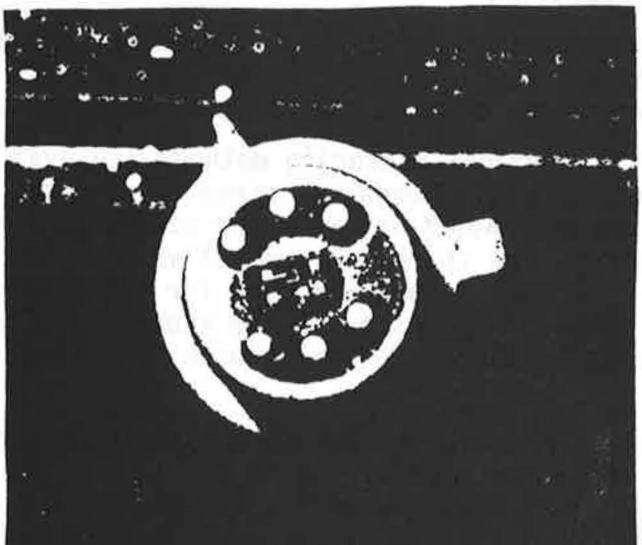

Fig. 2. Chemical sensor for ammonia.

Figure 2 shows the sensor of Sensistor AB, diameter 5 mm. The contact area of the sensor is the rectangular in the middle of the picture. The detection range of the sensor is 1-1000 ppm with a response time smaller than 1 s. The accuracy in the range between 4 and 500 ppm is ± 10%.

Primary produced to discover leakages a careful calibration of the sensors is necessary before application to animal houses.

Figure 3 shows the curves of calibration for the five sensors. The voltage decreases with increasing concentration. Every sensor has to be calibrated because of the great differences.

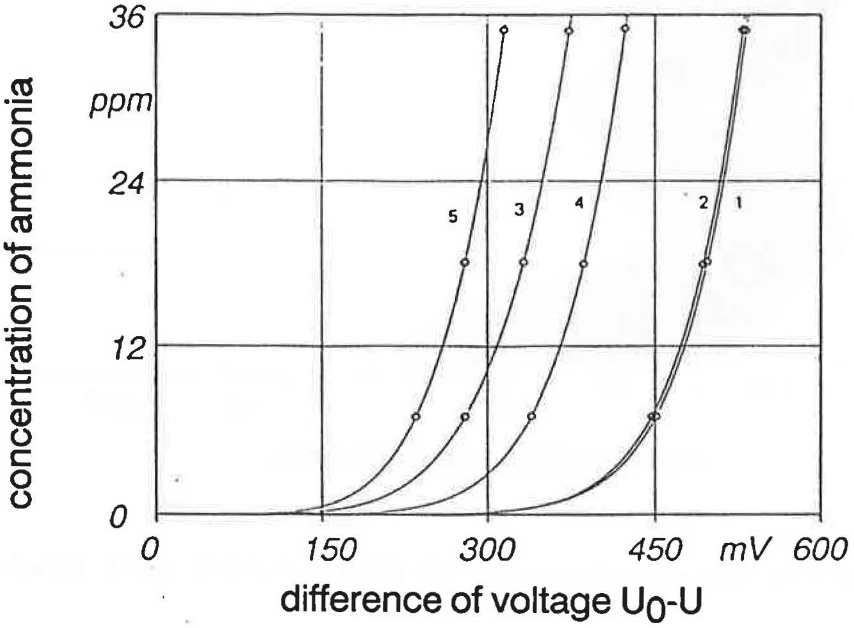

Fig. 3. Calibration curves for the five sensors we use in our studies.

Time-series measurements of ammonia concentrations

In pratice five sensors were located in an animal house for 37 days. The sensors measure the ammonia concentration in different heights above the floor during 24 hours the day. The vertical air velocity is registered in the outlet cell. At that time our aim was to test the practicability of such a technique. So we limited the expenditure. The data management was handled by a personal computer. Meanwhile we have increased the number of our sensor elements.

In Figure 4 the variations of ammonia concentration with height is shown. Each line belongs to one point of time. The time step is 5 minutes. We observe different concentration gradients from the bottom to the ceiling. The greatest gradients are caused by great ventilation rates. During the night the ventilation is low. The curves in the left part of Figure 4 have a smaller gradient in the floor zone than the curves in the right part.

In Figure 5 another day is shown. The curve tendency has changed. Few curves have the form of those in Figure 4 only. In Figure 5 most concentration curves do not alter with height significantly. This behaviour can be found in Figure 4, too, but on a lower level.

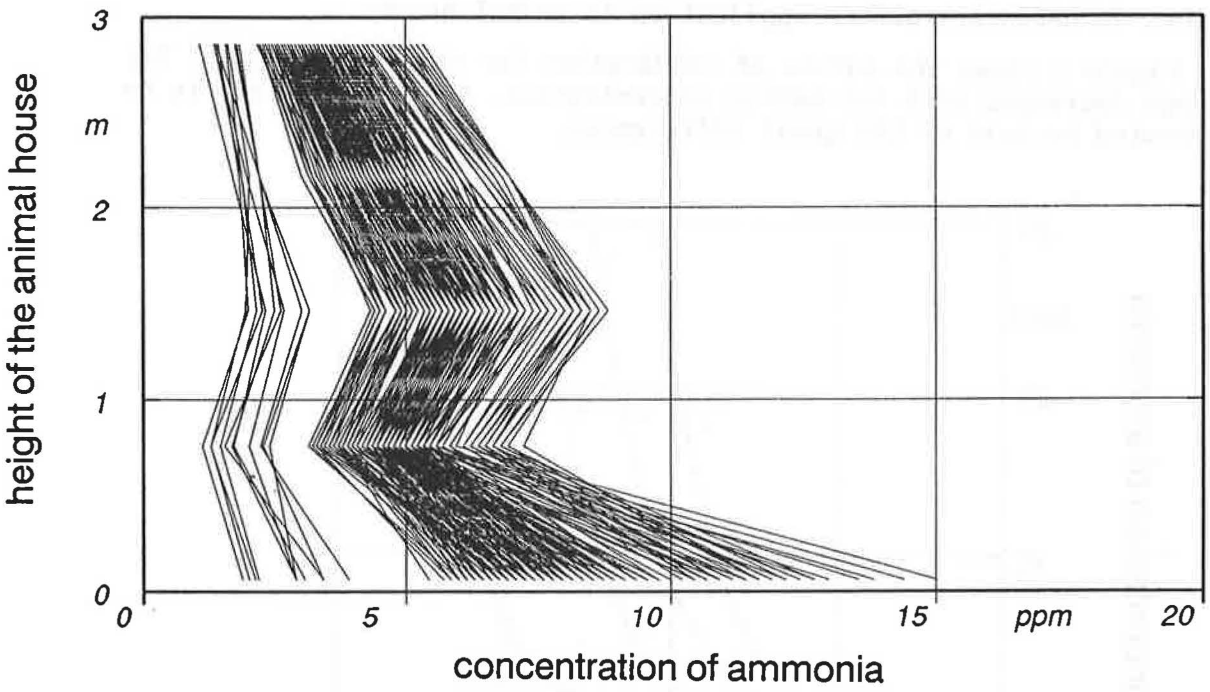

Fig. 4. Variations of ammonia concentration with height every 5 minutes on 07-28-1989.

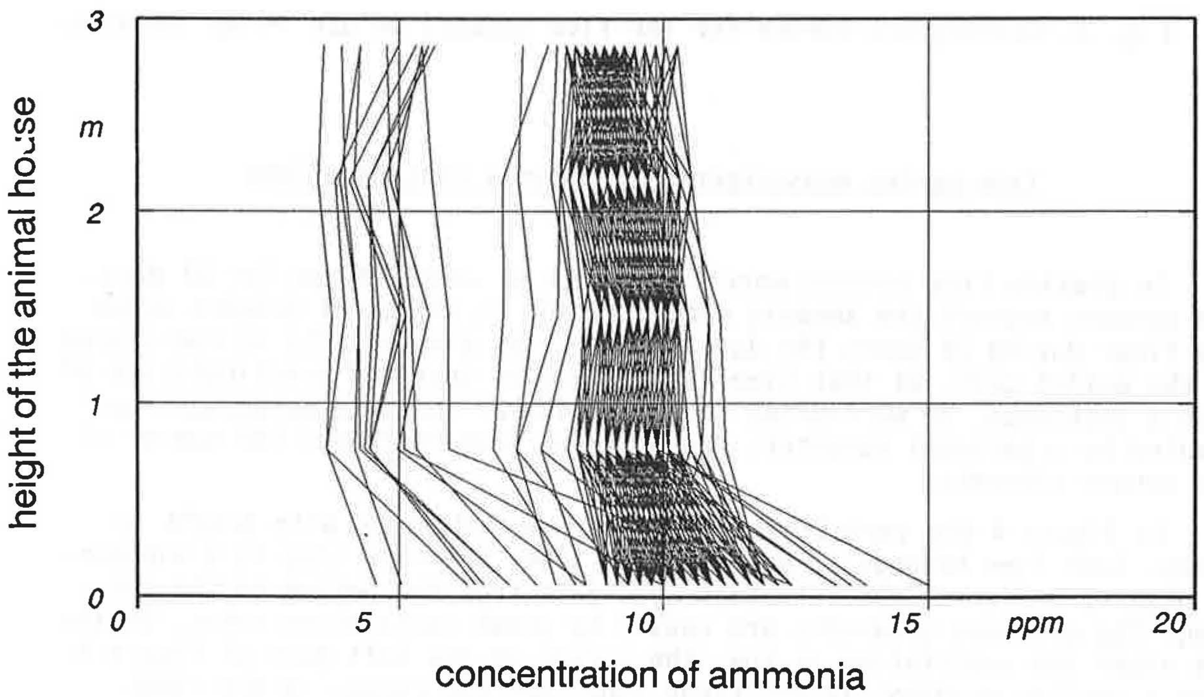

Fig. 5. Variations of ammonia concentration with height every 5 minutes on 09-01-1989.

The system of differential equations for the balance of mass and momentum is solved by a finite difference technique, called Marker-and-Cell (MAC) computing method, originally developed by Welch et al.(14,15). The flow region is covered with a rectangular mesh of cells. In x-direction we use 50 cells, in z-direction we have a partioning into 13 cells. The flow region is bounded by a layer of cells for setting boundary conditions: input and output of fluid.

The velocity conditions are set only. This is important to be mentioned: livestock buildings are dominated by suction ventilation. That means that we can set the boundary conditions in the outlet cells but the velocities in the inlet cells must be a result of the dynamic flow system. In the symmetrical case a manipulation is possible to set the velocities in the inlet cells, too, with regard to the mass conservation of the whole system. In the case of asymmetry it is not possible to predict the incoming velocities.

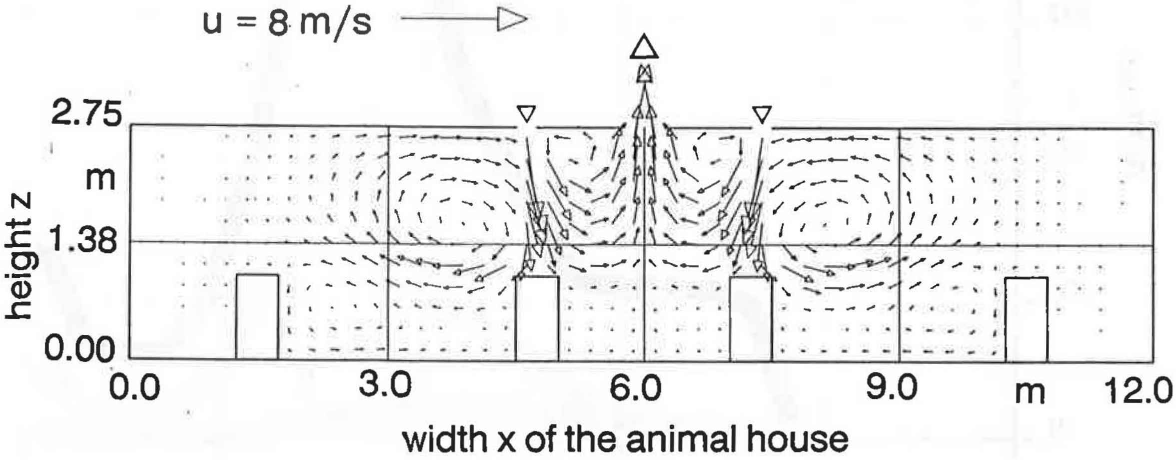

Fig. 6. Velocity vector field.

A numerical solution is obtained by advancing the field variables through several time steps. The results in this study are based on 5000 time steps. At each time step the calculation of all field variables is accomplished in two phases. At first approximate values of the velocity components are computed by purely explicit calculation. At the beginning of each cycle the data of the previous cycle are known. Mostly the principle of mass conservation with regard to a computational cell is violated. This inaccuracy is corrected in a second phase by an iteration method. The new velocities satisfy the zero divergence condition of continuity. So they can serve as initial conditions for the next time step and the foregoing procedure can be repeated again. The calculation is performed with double precision. The Reynolds number is approximately 10^6.

For example the velocity field after 9 s is shown in Figure 6. The air is sucked into the animal house through the inlet cells symmetrically. The air is emitted into the environment with 8 m/s. The incoming jets induce recirculating eddies. There is no direct convection flow from the ammonia sources to the outlet cell. With regard to Figure 1 we must conclude that the breathing zone of the animal (a) will not be loaded by high ammonia concentrations. On the other hand the emitted mass stream will be low. Similiar flow pattern in animal houses are published by Katz (14).

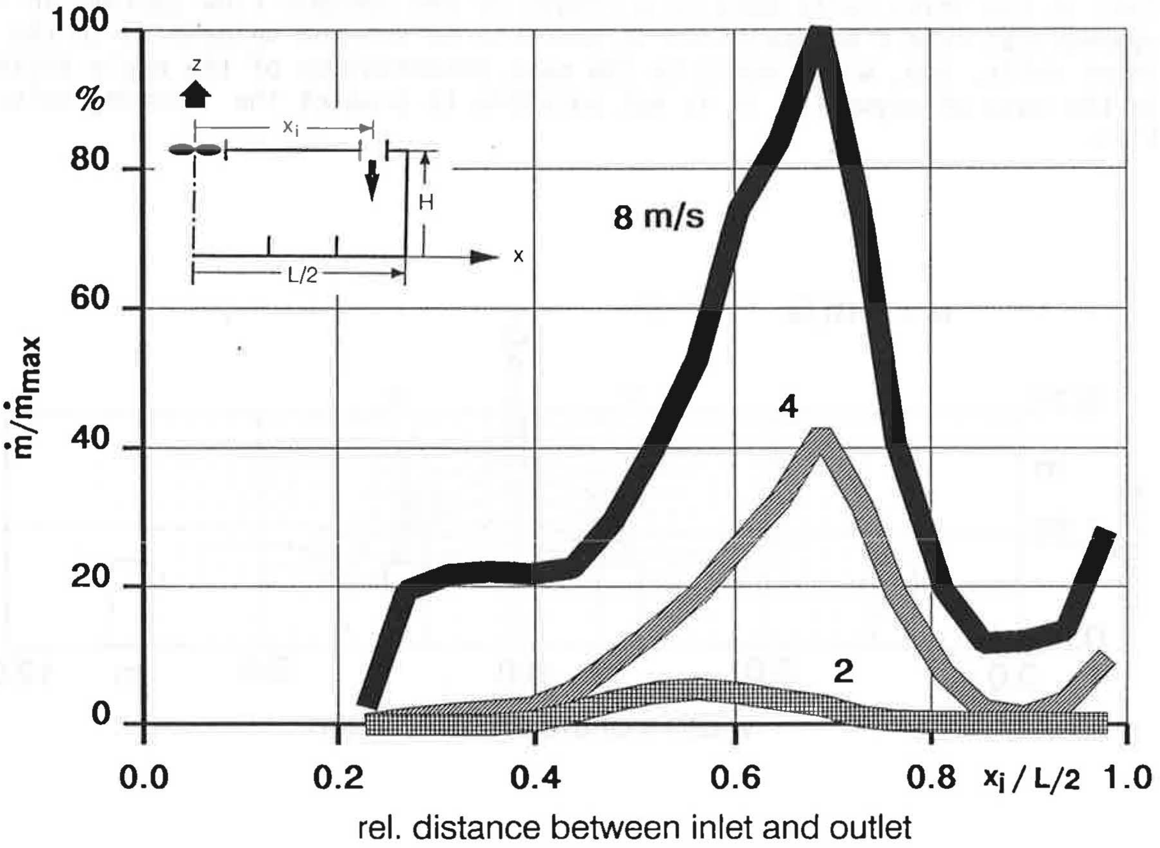

Fig. 7. Relative emitted mass stream consequential on the variations of the positions of inlet cells in the ceiling.

The flow patterns change when the positions of inlet cells vary. In Figure 7 and Figure 8 the simulation results are given. With this study we cannot quantify the real emission, but we can compare the different situations. From our first measurements of ammonia we estimate the diffusion coefficients as $D_x = D_z = 0{,}01\ m^2/s$.

The greatest output is given with the highest velocity. In Figure 7 the curves for 8 m/s and 4 m/s show a characteristic maximum. That means that we can supply the animal house with fresh air without causing great emission streams of ammonia. Altering the positions of inlets in the side-wall we can see in Figure 8 that minimum emission will occur when the inlets are just beneath the ceiling. In this situation the incoming air will not move to the bottom directly. In this first study it is assumed that there is an isothermal flow (17).

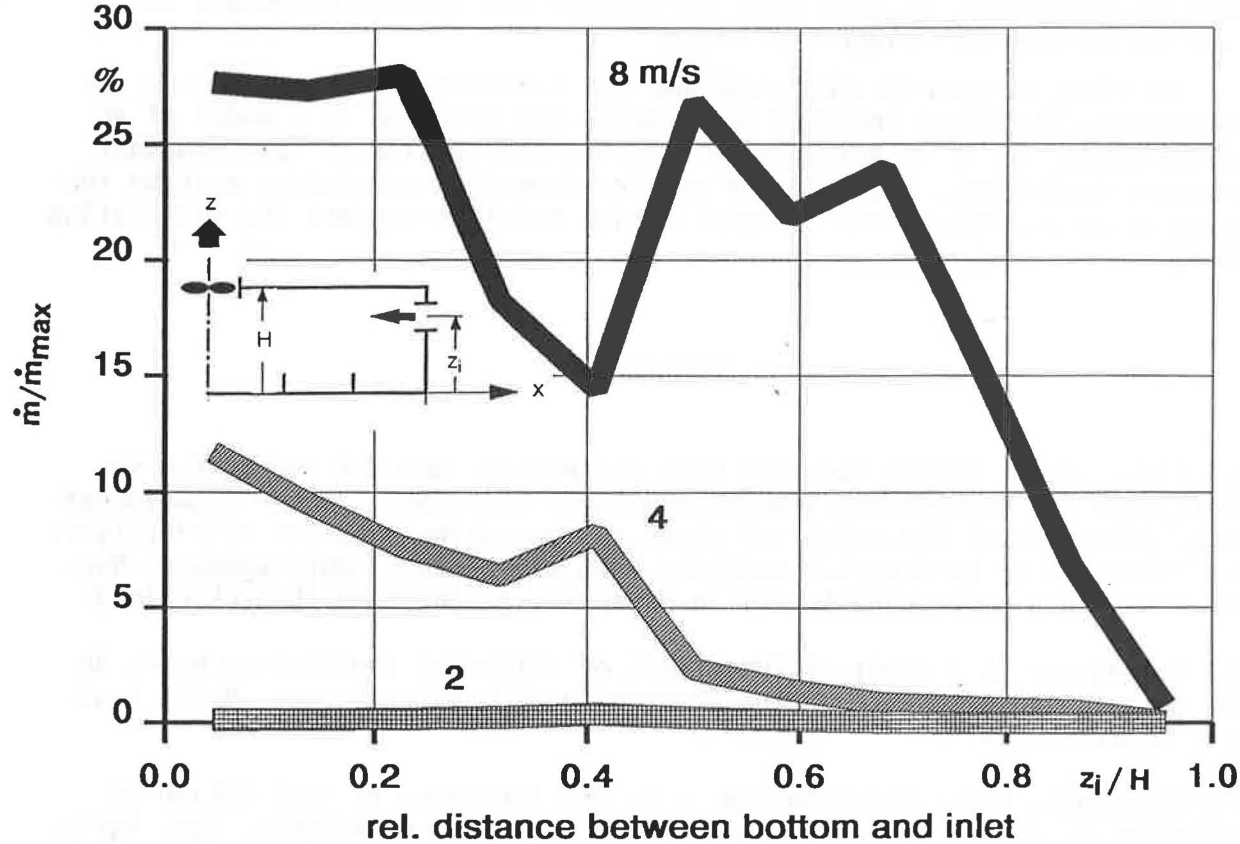

Fig. 8. Relative emitted mass stream consequential on the variations of the positions of inlet cells in the side-wall.

Conclusion

In order to reduce ammonia emission from animal houses it is necessary to know the local and temporal distribution of the ammonia concentration field. By numerical simulation this distribution can be calculated. But there is a lack of adaptation to real concentration fields. As yet real concentration fields of ammonia are not measurable with common measuring devices. First experiences with chemical sensors encourage us to look forward to a solution. It will turn out whether our special proposals for ventilation are only wishful thinking.

At first it must be clarified how the turbulent coeffients are to be determined. Therefore transfer experiments are prepared in a model of an animal house. So it is possible to simplify the problem by some constant boundary conditions. Secondly the complex numerical simulation must be substituted by a simple compartimentalization model to support the ventilation design.

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