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Dispersion of germs from animal houses and their relevance to immission

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Dispersion of germs from animal houses and their relevance to immission

Karl-Heinz Krause and Stefan Linke [1]

Abstract

The investigation of environmental load by emission from agriculture needs suitable dispersion models. Indeed there is no agro-physics, but there are special features in dispersion events of agricultural production that have to be taken into account. They start with wind induced sources and deflection conditions influenced by obstacles and end by unknown survival rates of germs and therewith vague risk assessment on immission site. Of course, for making decisions one cannot wait until all problems are solved irrevocably. But the pressure of administration to act may not lead to one-sided orientation as it happens at present in the model establishment of the TA Luft. We do not need imposed models but such that satisfy the reality conditions. Great deficits are observed with respect to agriculture.

Keywords: animal production, dispersion modeling, numerical simulation, risk assessment, TA Luft

Zusammenfassung

Zur Ermittlung der Umweltbelastung durch Emissionen aus der Landwirtschaft bedarf es geeigneter Ausbreitungsmodelle. Es gibt in der Tat keine Agro-Physik, wohl aber gibt es Besonderheiten bei den Ausbreitungsvorgängen in der landwirtschaftlichen Produktion, die es zu beachten gilt. Das beginnt bei wind- induzierten Quellen und hindernisbeeinflussten Ableitbedingungen und endet bei den unbekannten Überlebensraten von Keimen und damit einer vagen Risikoeinschätzung hinsichtlich ihrer Wirkung auf der Immissionsseite. Man kann bei Entscheidungsfindungen sicherlich nicht warten, bis alle Probleme unwiderruflich geklärt sind. Doch der Handlungsdruck in der Verwaltung darf nicht dazu führen, sich einseitig zu orientieren, wie derzeit bei der Modellfestschreibung in der TA Luft. Wir benötigen keine aufoktroyierten Modelle, sondern solche, die den Realitätsanforderungen genügen. Hier bestehen im Hinblick auf die Landwirtschaft sehr große Defizite.

1 Introduction

The agricultural production of plants and animals is characterized by emission of different air transported substances like gases, particles, germs, aerosols and several types of mixtures of them. While the emission rate in plant production is a seasonal one we have to recognize the nearly continuous output from animal houses. Both systems have in common that the airborne release takes place near to the ground. This means that structures of houses, plants and surfaces influence the transport mechanism of the emissions by the atmospheric wind. Furthermore the buoyant forces over the great areas of roofs of animal houses and over fields with different plant surface temperature cause vertical and horizontal motion at a small scale. Nevertheless, answers are expected to the questions where the emissions remain after they are released into the environment and what is their relevance to immission.

If the transport of airborne substances by the "vehicle" air is considered as mixture and not separately for multiphase flow, such a diffusion model is expressed by three mixture conservation equations of mass, momentum and energy and an additional one for concentration changes: the diffusion equation. Otherwise we have three field equations for each phase with three coupling jump conditions. Therefore correctly defined mixture quantities are of importance.

The mixture density ρ_M in a two-phase flow is given by

$$r_M = a\, r + b\, c \qquad (1)$$

c stands for the density or concentration of a single pollutant (phase 2), ρ is the density of the transport medium air (phase 1). The axiom of continuity requires

$$a + b = 1 \qquad (2)$$

With the definition of ρ_M and the mixture velocity vector $\mathbf{v}_M$

$$\mathbf{v}_M = \frac{1}{\rho_M}(\alpha\, \rho\, v + \beta\, c\, \mathbf{v}_C) \qquad (3)$$

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- $\mathbf{v}$ and $\mathbf{v}_C$ are the different phase velocities - the mixture continuity equation

$$\frac{\partial\rho_M}{\partial t} + \mathrm{div}\,(\rho_M\,\mathbf{v}_M) = \alpha\left[\frac{\partial\rho}{\partial t} + \mathrm{div}\,(\rho\mathbf{v})\right] + \beta\left[\frac{\partial c}{\partial t} + \mathrm{div}\,(c\mathbf{v}_C)\right] = \tag{4}$$

leads with

$$\beta = O\,(10^{-5}) \tag{5}$$

to the well known continuity equation of incompressible flows with $\mathbf{v}_\mathbf{M} = \mathbf{v}$

$$\mathrm{div}\,\mathbf{v} = 0 \tag{6}$$

The diffusion equation (continuity equation) for phase 2 is expressed by a source term S of mass generation and a diffusion term with the diffusion velocity $\mathbf{v}_\mathbf{CM} = \mathbf{v}_C - \mathbf{v}$

$$\frac{\partial c}{\partial t} + \mathrm{div}\,(c\mathbf{v}) = \frac{S}{\beta} - \mathrm{div}\,(c\mathbf{v}_\mathbf{CM}) \tag{7}$$

It is a question of pragmatism how to formulate the mass fluxes of each phase. In the case of $\mathbf{v} = \mathbf{0}$ molecular diffusion dominates the dispersion behaviour.

$$\frac{\partial c}{\partial t} + \mathrm{div}\,(c\mathbf{v}_\mathbf{C}) = \frac{s}{\beta} \tag{8}$$

According to Fick's law the mass flux $c\mathbf{v}_\mathbf{CM}$ is proportional to the gradient of the concentration of matter:

$$c\mathbf{v}_C = -\,D\ \mathrm{grad}\ c \tag{9}$$

The coefficient of proportionality D is the (constant) diffusivity. The diffusion equation in Cartesian coordinates is

$$\frac{\partial c}{\partial t} - D\ \mathrm{div}\,(\mathrm{grad}\ c) = \frac{S}{\beta} \tag{10}$$

The operation div grad refers to the Laplace-Operator:

$$\mathrm{div\ grad} = \Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{11}$$

The molecular diffusivity D is of the order of 0.2 $\mathrm{cm^2/s}$ for air and 10^{-5} $\mathrm{cm^2/s}$ for water. Diffusion can be defined as an irreversible process by which matter, particles, germs, populations, etc. are distributed according to individual random motion. Each individual moves a short distance λ in an arbitrary direction in a short time τ. Diffusion occurs from high concentration to low concentration. λ and τ are small in comparison e.g. with the time scale t and the length scale x in an Eulerian coordinate system.

2 Atmospheric diffusion

There are many diffusion systems with a non-zero velocity field $\mathbf{v}$. So the atmospheric diffusion is influenced by different wind field aspects. The velocity vector field $\mathbf{v}$ (u, v, w) is splitted to its average $\mathbf{V}$ (ensemble mean) and an fluctuation part $\mathbf{v}'$

$$\mathbf{v} = \mathbf{V} + \mathbf{v}' \tag{12}$$

and the scalar concentration c in an adequate manner to

$$c = C + c' \tag{13}$$

The result of substituting (12) and (13) into (7) in combination with (10) and averaging by using the Reynolds postulates, e.g.

$$\overline{c'} = 0,\ \overline{C} = C,\ \text{etc.} \tag{14}$$

is

$$\frac{\partial c}{\partial t} + \mathrm{div}\,(C\mathbf{V}) + \mathrm{div}\,(\overline{c'\,\mathbf{v}'}) = \frac{S}{\beta} \tag{15}$$

In analogy to the kinetic theory of gases the average product is related to the average concentration gradient, compare with (9):

$$\overline{c'\mathbf{v}'} = -\mathbf{K}\ \mathrm{grad}\ \mathbf{C} \tag{16}$$

where $\mathbf{K}$ is a 3x3 turbulent diffusivity tensor (Csanady, 1973). The tensor elements are determined from fluid flow analysis (Spaulding, 1976). In comparison with (9) the magnitude of $\mathbf{K}$ in horizontal direction is of order 10^4 $\mathrm{cm^2/s}$. The atmospheric diffusion

$$\frac{\partial c}{\partial t} + \mathrm{div}\,(C\mathbf{V}) - \mathrm{div}\,(\mathbf{K}\ \mathrm{grad}\ C) = \frac{S}{\beta} \tag{17}$$

involves no specific quality that refers to the emitted substances apart from source data and deposition velocities. It does not matter whether vanillin, ammonia or germs determine the atmospheric pollution provided that there is no relative motion caused by drag (Margolin, 1977). The calculation of immission is always the same. (17) can be solved generally by numerical methods only.

The numerical solution contains errors by numerical diffusion. Sklarew has shown that these effects can be avoided by introduction of an effective velocity (Hotchkiss, 1972)

$$\mathbf{V}'' = \mathbf{V} - \mathbf{K}\frac{\nabla C}{C} \qquad (18)$$

The handling of problems works well when ∇C is resolved by a sufficient number of cells. In regions of strong flow distortion and poor resolution errors in the concentration distribution are obtained. The modeling of source constellation must be taken into account with care. In the following figures there is high resolution in the vicinity of buildings. Even the emitted mass flow is produced partly with vortex structures of the flow field in the stack outlet.

An alternative approach to (18) is to replace the diffusion velocity - $\mathbf{K}\ \nabla C/C$ by a random velocity $\mathbf{V_R}$ (Zanetti, 1990) :

$$\mathbf{V_R} = -\mathbf{K}\frac{\nabla C}{C} \qquad (19)$$

The sum of $\mathbf{V}$ and $\mathbf{V_R}$ is the total equivalent transport velocity.

$$\mathbf{V}'' = \mathbf{V} + \mathbf{V_R} \qquad (20)$$

The diffusion equation reduces to the form

$$\frac{\partial c}{\partial t} - \operatorname{div}(C\mathbf{V}'') = \frac{S}{\beta} \qquad (21)$$

The original problem of turbulent atmospheric diffusion is transformed into one describing the advective change of fluid density C in a compressible fluid moving with the fictitious velocity field **V''** (Sklarew, 1971). The original boundary conditions have to be transformed. The physical space is divided into cells of a fixed Eulerian spatial grid and the particles carry pollution from cell to cell forced by the fictitious velocity field. This velocity field is not a solenoidal one, that means that the condition of conservation of mass is not fulfilled. So particles will move to maintain balance of mass. An uneven distribution of particles determines the average cell concentration.

There exists a hybrid method of Eulerian and Lagrangian techniques to solve the atmospheric diffusion equation. It is called **P**article-**I**n-**C**ell making use of the **K**-theory approximations ("**PICK**"). The Eulerian grid size determines the maximum spatial resolution. It is used for winds and values of concentration. Phenomena within grid size like point emissions can be represented by particles. The Lagrange approach for the modeling of dispersion is based on the calculation of the spatial trajectories of virtual particles moved with random velocity $\mathbf{V_R}$ (Janicke, 2001).

3 Significance of the flow field

Air pollution modelling is in general based on observations and theories of the surface layer (Nieuwstadt, 1981). The restriction to analytical solution of the governing equations in terms of known functions is lifted more and more by solving differential equations by digital computers directly. But the required resolutions with a great number of grid points damp the optimism. Turbulent flow contains eddy sizes from magnitude of 500 m to 1 mm. With respect to the conservation of momentum in a range of 10 km length, width and height 10^{18} grid points would be needed. But the resources are limited.

Figure 1 shows the dispersion of ammonia in the narrow surrounding of animal houses. Roughly 1.4 million cells are needed for this simulation. The Eulerian model technique is used. The pressure distribution around the buildings and the turbulence induced mechanically determine the distribution of ammonia, odour etc. It is a typical situation in a village (Krause, 2002).

In figure 2 the air motion around a broiler house is visualized by trajectories. It is intended to build a broiler house 60 m eastward from a little forest. A small valley lies between forest and broiler house. The trajectories show a complex velocity field. Here we need no surface layer contemplation, we need a detailed velocity field. Without a real velocity background Eulerian and Lagrangian modeling are senseless.

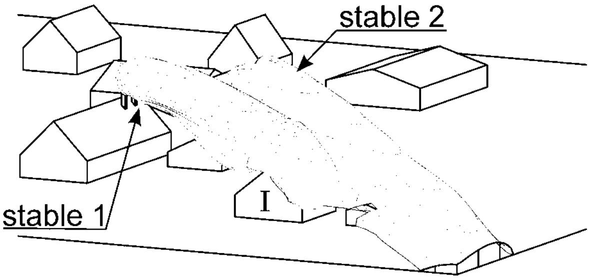

Figure 1:
Two stables emit air at low height over roof. The ammonia concentration amounts to 10 ppm. 5,040 m^3/h are thrown out at the front stable at every flue with a velocity of w_0 = 5.6 m/s, at back stable there are 4,224 m^3/h with a velocity of w_0 = 4.7 m/s. The shell areas of equal concentrations refer to C_0 = 0.14 ppm. The wind speed is U_{10} = 3 m/s at a height of 10 m. The puff is deflected. The building at the immission point I is coated by the ammonia puff.

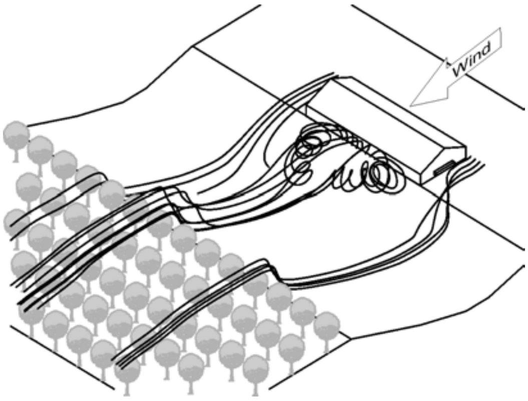

Figure 2:
Particle pathes (trajectories) around a broiler house. The wind blows from the right side perpendicular to the ridge line. On the lee side, that means in the shelter area behind the building, we observe strong turbulences that are mechanically induced. The stable air is thrown out at the gable in front of the perspective picture. This fact causes no symmetrical flow around the stable. A small deflection takes place to the gable in front. This is a typical example of obstacle influenced releases by near ground sources of agricultural animal production. It makes a great difference whether the stable air is emitted at the roof or at the gable. The difference is given by the initial distribution of ammonia concentration: by roof release we have so-called point sources with high density of ammonia, by near ground release we have so-called area sources with a great effect on the dilution when the air is ejected to the ground. The ground acts like a crash plate with respect to the mixing of stable air with the air in the surrounding.

The importance of a real velocity field is demonstrated by the turbulent viscosity at ground (figure 3) and at a small distance above ground (figure 4) induced by flow separation. The consequences are expressed by quite different ammonia distributions with respect to the forest (Krause, 2001). Figure 5 shows the broad ammonia puff around the broiler house with the isoarea of 10^3 µg/m^3. If the ammonia is exhausted vertically at the gable (figure 6) the forest is loaded hundred times higher then in the first case. Nevertheless, the administration decided to eject the stable air at the gable in vertical direction.

Figure 7 shows a so-called wind induced source, an outdoor climate stable (Krause, 2001). It is a very sensible system with respect to wind flow. We must learn to develop a feeling to the special problems of agricultural production. Crude simulation programs are misleading.

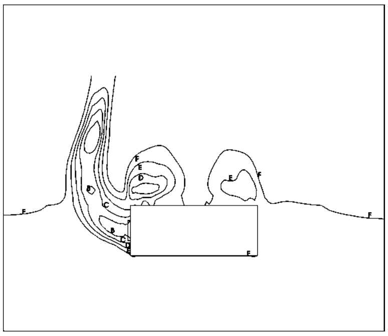

Figure 3:
The flow around the broiler house causes turbulence structures, top view of figure 2. The isolines of turbulent viscosity μ_T are pointed out at a height of 0.5 m above ground. The letters refer to the following values μ_T in 10-2 Pa s (= N s/m²)
A = 6.1, B = 5.08, C = 4.07, D = 3.05, E = 2.04, F = 1.02. In comparison the dynamic viscosity µ of air at 10 °C amounts to 1,81 10^{-5} Pa s. At the outlet on the left side we have a great production of vortices

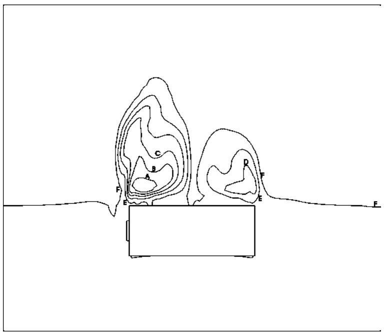

Figure 4:
The isolines with the same level of figure 3 are found in the shelter of the broiler house, here at a height of 3 m above ground

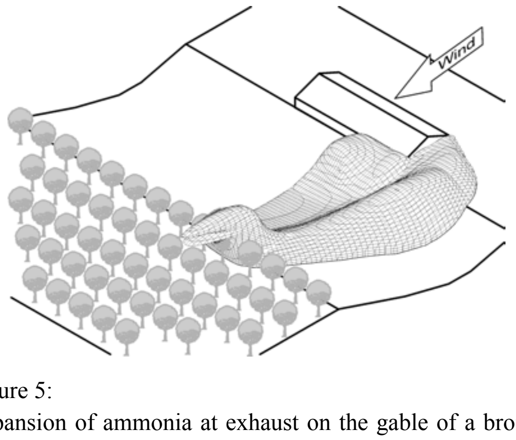

Figure 5:
Expansion of ammonia at exhaust on the gable of a broiler house. Perspective presentation of the isoarea of 10^3 µg/m^3. The exhaust air is blown out downwards on the gable wall in front. The concentration of the outer mantle of the cloud of ammonia shows a dilution of 0.001 compared to the outlet concentration

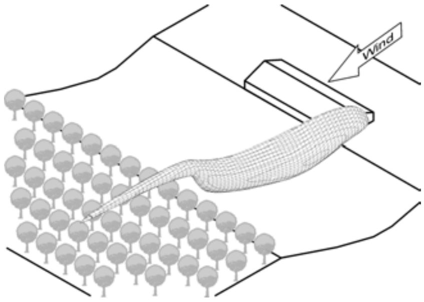

Figure 6:
Perspective view of the visible made cloud of ammonia induced by the emission from the broiler house and the windfield. The exhaust air is blown out upwards on the gable wall in front. The concentration of the outer mantle from the cloud of ammonia shows a dilution of 0.1 compared to the outlet concentration. The wind velocity has a magnitude of 2.5 m/s in a height of 10 m

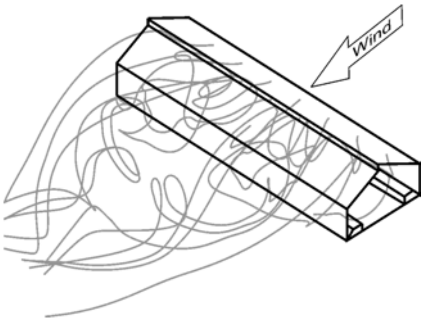

Figure 7:
Perspective presentation of an outdoor climate stable with shed roof. All length sides are covered with wind break nets. The opening in the ceiling can be closed or covered with a wind break net, too. The wind flows in optimal manner vertically to a side wall with a velocity of 4 m/s in a height of 10 m. The vertical flow is distributed as parabola profile. Different trajectories are shown beginning in the windward opening. The shed roof is open

4 Estimation of immission loads

To have confidence in simulation techniques does not prevent from plausible controls of results. In the VDI guidelines "Emission Control - Livestock Management - Pigs" (VDI 3471) and "Emission Control - Livestock Management - Hens" (VDI 3472) the so-called odour threshold distances were derived empirically. This is the distance at which - on approaching the facility - a facility-typical smell is first perceived or identified (Schirz, 1989). The distance r is described by

$$r = 48{,}69\ M_{T,eq}^{1/3} \tag{22}$$

for optimal equipment. $M_{T,eq}$ is the odour-relevant total livestock mass value. At the distance r the source odour concentration C_0 is deluted to the threshold concentration $C_S = 1$ OU/m^3 and below:

$$q = \frac{C_0}{C_S} \tag{23}$$

The factor q alters from q = 350 in the surrounding of piggeries to q = 80 in the surrounding of cattle houses (Schirz, 1989). Improvements of the olfactometry measurement double the q-values nearly (Brose, 2001). The dilution factor q is valid not only for odour but also for ammonia, germs etc. The consequence is explained by the example of ammonia emission from swine houses. The average emission factor E (Umweltbundesamt, 2002) is

$$E = 3 \frac{\text{kg}}{\text{year animal} - \text{place}} \tag{24}$$

With an average pig mass of 70 kg and the Live mass Unit LU (= 500 kg) F is transformed to

$$E = 2.45 \frac{\text{g}}{\text{h LU}} \tag{25}$$

With a mean specific volume rate (Pedersen, 1998) of 300 m^3/(h LU) the source concentration is determined to

$$C_{0,NH_3} = 8.2 \frac{\text{mg}}{\text{m}^3} \tag{26}$$

Applying to (23) with q = 2 · 350 = 700 the ammonia immission concentration is

$$C_{NH_3} = \frac{C_{0,NH_3}}{q} = 11.7 \frac{\mu\text{g}}{\text{m}^3} \tag{27}$$

neglecting deposition. Tab. 1 shows the values for different livestock systems. The immission concentration must be compared with threshold values.

Doing so several aspects are worth to be mentioned. The natural background concentration of ammonia is about 4 µg/m^3, in rural areas 14 µg/m^3. Therefore it is a highly risky undertaking to demand threshold values below those values at the odour threshold distance, see tab. 1. On the other hand the question arises whether the factor q in (23) is of correct magnitude; perhaps it is to small and there is no ammonia problem at the odour threshold distance. With regard to germs we have the same situation as in the case of endotoxin. There are no known threshold values. All these statements base on the assumption of the atmospheric diffusion equation that the same dilution factor q is valid for all airborne gaseous substances from animal houses.

Table 1:
Immission concentration of different pollutant at the odour threshold distance. Though it is allowed to build a house or to live nearby animal houses, it may be forbidden with respect to ammonia to arrange a sensible ecosystem, because the threshold value of 10 µg/m^3 is exceeded. On the other hand the immission concentration stayed 93 per cent below the odour threshold value of 1 mg/m^3. In a piggery the mass of 60 LU causes an ammonia emission of 1.29 Mg/Jahr. After TA Luft the minimum distance X_{min} is calculated to $X_{min} = (41{,}668 \cdot 1.29)^{0,5} = 232$ m. The odour threshold distance according to (22) is 166 m

Species	factor q	mean specific volume rate in m^3/(h LU)	**ammonia**			**endotoxin**		
			emission factor E in g/(h LU)	Source concentration C_0 in mg/ m^3	**immission concentration C in µg/ m^3**	mean respirable emission in µg/(h LU)	Source concentration C_0 in ng/ m^3	**immission concentration C in ng/ m^3**
cattle	160	150	1.7	11.3	70.6	1.2	8	0.05
pig	700	300	2.45	8.2	11.7	5.9	20	0.03
poultry	760	750	2.8	3.7	4.9	42.7	4	0.005

5 Conclusion

Better solutions are enemies of good ones. Indeed the Gaussian plume model is a first approach to estimate immission loads by analytical solution of the atmospheric diffusion equation. The development of efficient grid generators, the improvement of computational methods and the progress in computer based solutions broaden the possibilities to elaborate more precise statements to environmental problems. The update of the TA Luft reveals a great dilemma: to improve the immission prognosis by substituting the Gaussian model by a Lagrangian one is no real progress because of the lack of realistic flow field calculation. From this point of view the Lagrangian model AUSTAL2000 with a meteorological flow background of the planetary boundary layer does not realize the situation of agricultural production with complex flow situation in the surrounding of animal stables. Furthermore there is a great lack of ammonia immission data of the surrounding of animal houses to validate dispersion models.

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