

Compartmental Airflow Simulation in Stables with Natural Ventilation

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Abstract

The assessment of air volume flow rates is important in estimating the environmental impact of airborne emissions from stables. In contrast to mechanically ventilated stables the amount of air exchange is variable in open stables and depends on the wind velocity and wind direction.

Statistics on the emission mass flow of naturally ventilated stables are not available, improvements for analysing the measured data are necessary. This work shows a new method to overcome these disadvantages. The used calculation method is applied in the medical area since some decades but for the first time in agriculture to calculate the air volume flow. The method of compartmentalisation increases the quality of air flow calculation measurements and gives the possibility to check the results of other techniques. This allows to define and decrease the error level.

Keywords: compartment, airflow simulation, air change, tracer methods, natural ventilation

1 Background

In Europe most agricultural animals live in stables. These stables are often near living areas. Sometimes the neighbourhood receives (much) odour nuisances which can induce a lot of problems. Therefore, the distance between a stable and its neighbourhood (e.g., dwelling houses) which is necessary to avoid odour loads, must be determined. To estimate the actual value of odour output of a stable into the environment it is necessary to calculate the odour mass flow. This can be done by measurements or by simulations. If we take measurements in animal stables we have to distinguish between different forms of ventilation.



Figure1: Ventilation forms in agriculture. Left side: mechanical ventilation, Right side: natural ventilation

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2 Ventilation forms in agriculture

In agriculture we have two ventilation forms: mechanical and natural ventilation. In case of mechanical ventilation (Fig.1, left side) the leaving air is transported by ventilators into the environment. The number of ventilators is known, a high accuracy in calculation of the air volume flow is possible.

In case of natural ventilation (Fig.1, right side) there is no regulation mechanism for the air volume flow. The atmospheric conditions wind velocity and wind direction have a direct influence on the stable climate. For example an exchange surface (window or other opening) could be an entry and in the next moment an exit.

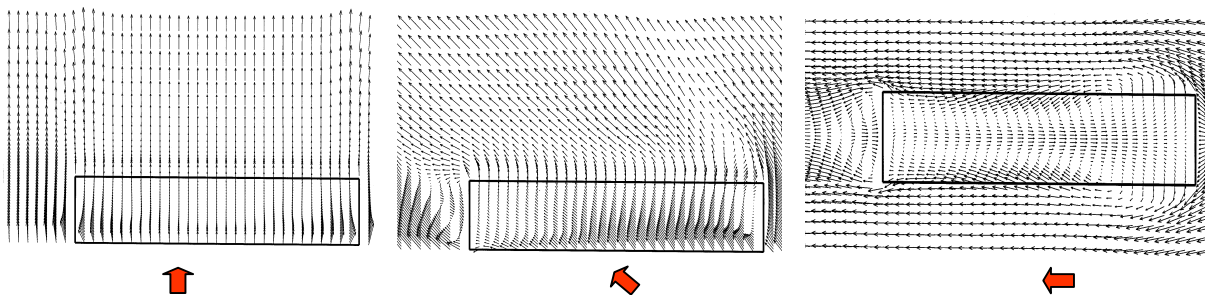


Figure 2: Air flow patterns (1.5 m above the ground) in a stable with natural ventilation at different wind directions: transverse flow (left), diagonal flow (middle), lengthwise flow (right)

Figure 2 shows the dependency of natural ventilation on wind direction. These pictures are results of numerical simulations. The length of an arrow characterizes the air velocity, the arrow angle the air direction. As the three pictures demonstrate the air flow pattern inside varies with changing wind direction. In case of mechanical ventilation (not shown here) there is no or little dependency of air flow on atmospheric parameters.

3 Basics

The emission mass flow of a gas is the product of two factors: gas concentration C and air volume flow \dot{V} . Both factors depend on time t .

$$\dot{m} = C(t) \cdot \dot{V}(t) \neq C(t) \cdot \dot{V}(t) \quad (1)$$

The measurement of the two factors is usually performed at suitable measuring locations in a stable and/or at an exchange surface. The error potential during concentration measurements will not be discussed in this work. The calculation of the necessary mean air volume flow in case of natural ventilation is problematic as written above.

In a small number of cases a direct calculation of the product “wind velocity • exchange surface” is possible. However, tracer methods as indirect methods are preferred to estimate the air flow in naturally ventilated stables. The most important indirect tracer methods are described in the following.

3.1 Fixed tracer gas injection

The tracer gas is injected continuously with a constant concentration during the whole measuring period. At the sampling points, which represent the probable points of the outgoing air, the gas concentration is analysed. Because of the different air change the sampling concentration varies. The measured values are considered as (inverse) proportional to the air change rate.

3.2 Variable tracer gas injection

The tracer gas is injected into the stable at given injection points. The target of this method is to give a continuous tracer concentration at the sampling points. Therefore a feedback control of the tracer gas flow at the injection points is needed, which requires high-level automation equipment. At present the application of the variable tracer gas injection is limited to the area of research and development.

3.3 Decay method (used method)

The tracer gas is injected suddenly into the stable space. At defined measuring points the decay of the homogeneous initial concentration is recorded at the same time. With the decay behaviour the air change rate or the air flow can be evaluated.

The air change rate α [Unit: 1/Time] can be calculated by equation 2:

$$\alpha = \frac{\ln(\overline{C}_s) - \ln(\overline{C}_e)}{t_e - t_s} \quad (2)$$

C represents the concentration, t the time, whereby the indices indicate the start time “s” and the end time “e”. $\overline{C}_s = \frac{C_s}{C_i}$ and $\overline{C}_e = \frac{C_e}{C_i}$ are the ratios of the start- resp. the end-

concentration to the injected tracer concentration. A tracer must fulfill a lot of conditions, for example not toxic, small background concentration and easily detectable. Common tracer gases are Sulfurhexafluorid (SF₆) or Krypton 85.

Each sampling point delivers a local air change rate. From these local values the overall air flow is usually calculated by taking the average of all measured values. However, the interpretation of the different air change rates is difficult. Especially cases of changing wind velocities and wind directions require a careful check of the results.

The following simulations shows that the usual procedure of averaging local air flow rates leads to large errors.

4 Simulation

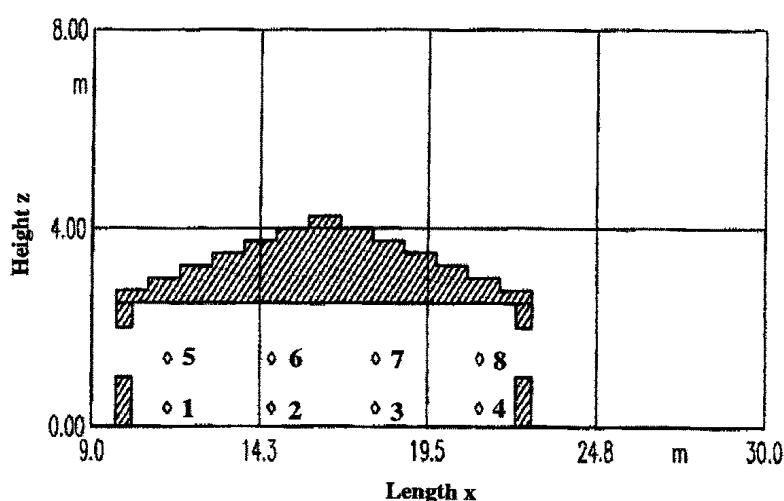


Figure 3: Cross-section of an open stable with marked measurement locations.

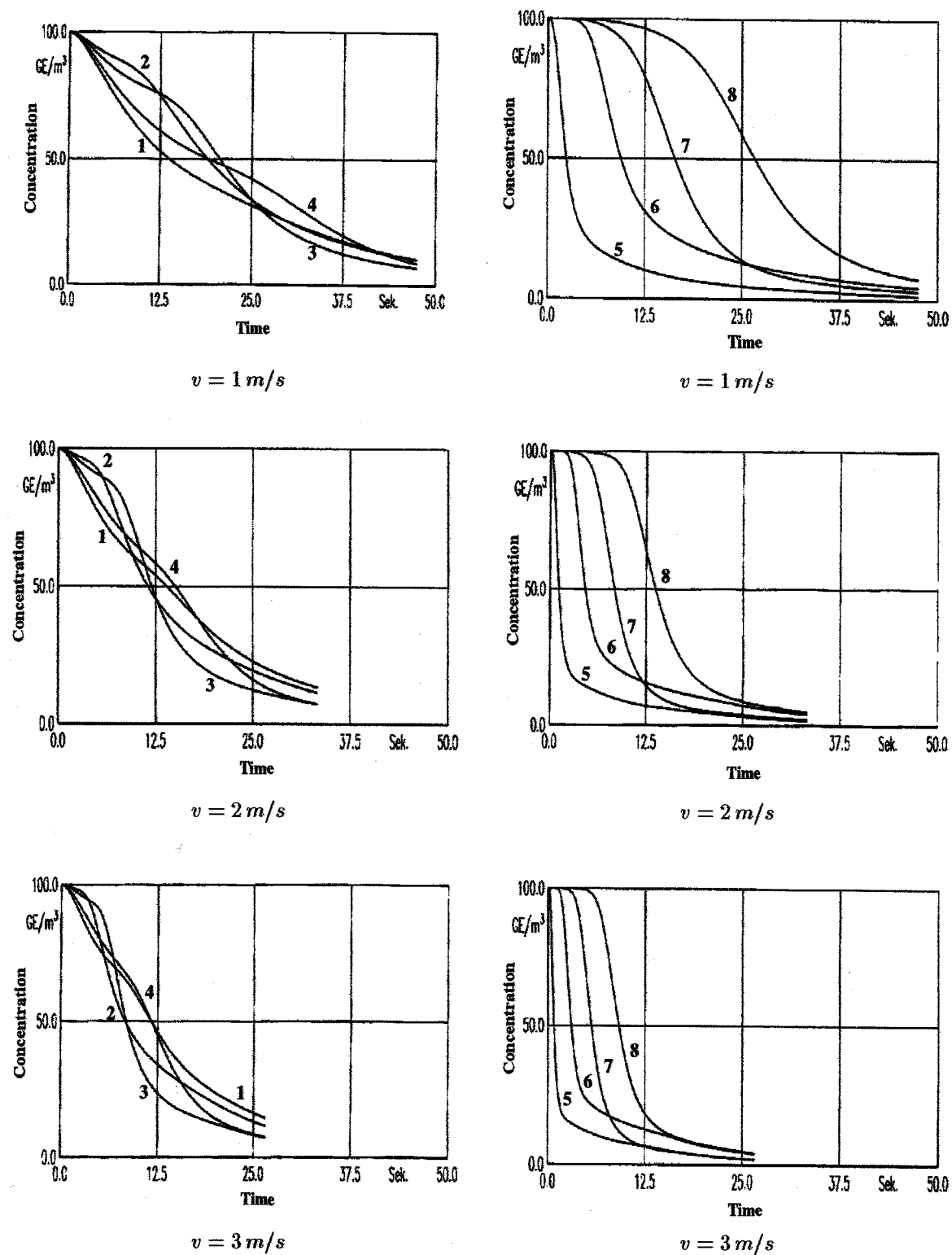


Figure 4: Decay functions of odour concentration at different measurement locations 1-4 and 5-8 by a simulation with $v = 1 \text{ m/s}$ (top), $v = 2 \text{ m/s}$ (middle) and $v = 3 \text{ m/s}$ (bottom).

Figure 3 shows a two-dimensional centric cross-section of an open stable. Eight measuring points of the tracer concentration are shown. The lower and upper measuring points are at heights of 0.4 m resp. 1.4 m above the ground. The open stable is provided with a windward and a leeward opening of 1 m height. The interior width of the stable is 12 m, the height 2.5 m.

The wind flow is from the left hand side with wind velocities of 1, 2 or 3 m/s. The initial concentration amounts to 100 odour units/m³. The measuring points 1 and 4 are situated opposite from the inlet resp. the discharge openings. The points 2 and 3 are situated in the center of the stable.

The upper measuring plane is in the direct flow zone. It can be expected that measured tracer concentrations will be very different between the planes and that the differences within each plane will be less distinct.

Evidently the S-formed decay takes place very slow in the lower measuring plane (points 1 to 4). In contrast to this, in the upper measuring plane (points 5-8) always a steep concentration decay is apparent up to 10% of the final values.

On the basis of the decay behaviour of the tracer concentration at the measuring points 2 and 6, which are selected representatively from the upper and lower plane in Figure 4, it will be shown how dubious the determination of the air change rate can be on the basis of averaged decay constants.

Measuring point 2 is in the lower, measuring point 6 in the upper level. For the selected example the following continuity equation is valid:

$$v \cdot A = \alpha \cdot V \quad (3)$$

A represents the surface of the side wall openings, V the stable volume, v the wind velocity. The exact α -values for the different wind velocities are:

for $v = 1 \text{ m/s}$: $\alpha = 0,033 \text{ s}^{-1}$,
 for $v = 2 \text{ m/s}$: $\alpha = 0,066 \text{ s}^{-1}$,
 for $v = 3 \text{ m/s}$: $\alpha \approx 0,1 \text{ s}^{-1}$.

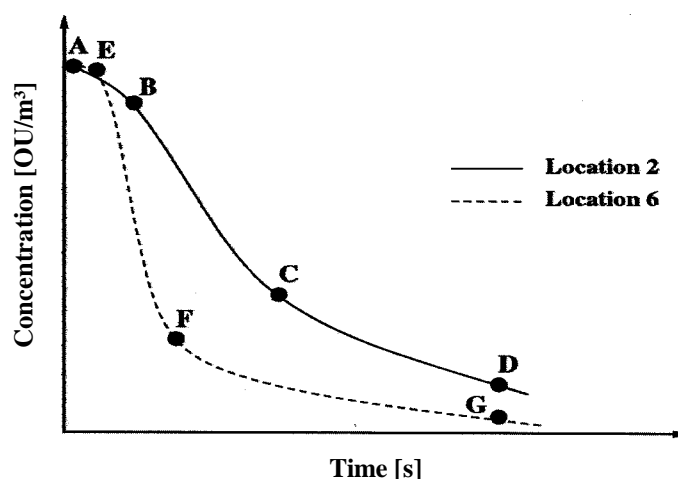


Figure 5: Decay functions of odour concentration at measurement locations 2 and 6 to determine the air change rate at different sections by $v = 2 \text{ m/s}$.

Table 1 lists the calculated values for α (determined from simulation data) for $v = 1, 2$ and 3 m/s, resp., of the indicated sections in Figure 5.

Table 1: Air change rate calculated from two decay functions (locations 2 and 6) at different sections by $v = 1, 2$ and 3 m/s.

Wind velocity (m/s)	Location 2 lower plane			Location 6 upper plane	
	A-B	B-C	C-D	E-F	F-G
1	0.018	0.060	0.052	0.135	0.071
2	0.016	0.087	0.058	0.237	0.125
3	0.008	0.116	0.073	0.345	0.144

Which function distance should be regarded as representative for the calculation of the air change rate α ? It is very doubtful to pick out a curve a priori as generally accepted. Conclusion: it is not possible to estimate the air flow by an average air change rate [1, 2].

5 Compartmentalisation

If one does not only take the decay functions of tracer concentration but also considers the mass conservation in the whole system the air change rate can be determined precisely. This will be demonstrated in the following.

5.1 Basics of compartmentalisation

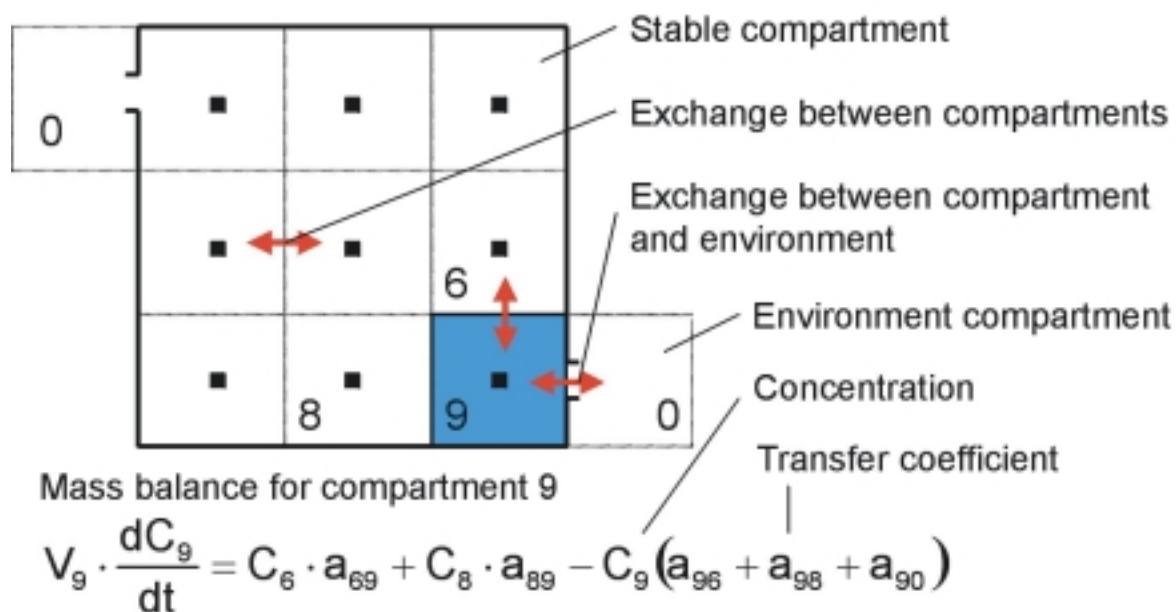


Figure 6: Principle of compartmentalisation – mass balance and transfer coefficients

In contrast to the decay method an inhomogeneous tracer initial concentration is assumed. With view on the shown simulation examples this assumption is more realistic. The stable is divided into several virtual compartments [3, 4] which can have different volumes. In the middle of each compartment there is a measuring point for the tracer concentration as function of time. The initial tracer concentration in each compartment is assumed to be homogeneous. In comparison to numerical simulation the room (stable) is not divided into a large number of small compartments (see Figure 7). This means, that we make a macroscopic consideration.

The aim of the used compartmentalisation is the calculation of the air volume flow and the air flow pattern inside a stable with limited measuring techniques (small numbers of measuring points).

Figure 6 shows the principal way of compartmentalisation. An exchange of tracer mass can only occur through the exchange surfaces to the bordering compartments and the system environment (9 to 0). An input of tracer mass into the stable is not possible. The exchange value with a stable border (wall etc.) is zero.

As shown the example for compartment no. 9 in figure 6, balance equations for each compartment must be formulated. On the left hand side (figure 6) there is the change of tracer concentration with the time and the specific compartment volume. On the right hand side the exchange of tracer mass between neighbouring compartments is denoted. The transport of tracer mass is characterised by (unknown) transfer coefficients. If we consider the two compartments 8 and 9 then two transfer coefficients exist (a_{89} und a_{98}). Because both transfer coefficients are located in both equations (the equation for compartment 8 is not written here) we get a linear connected system of equations which can be solved by a suitable algorithm. Negative unknown transfer coefficients mean a loss, positive a win of tracer mass for the specific compartment.

In contrast to the decay method we don't get an average air flow but an absolute air flow. The reason: all time steps¹ are considered. For more detailed information about the equations and the algorithms please read [5].

5.2 Results of compartmentalisation

Figure 7 shows a theoretical example of a cross-section of a 2-dimensional room. The fresh air flow comes in at the left top side and leaves the room at the bottom of the right-hand wall. A part of the main air flow goes back towards the inlet. In the middle of the room there is an area of low velocity. Is the method of compartmentalisation able to calculate the correct air flow?

¹ Time interval between two measuring values of tracer concentration at each measuring point
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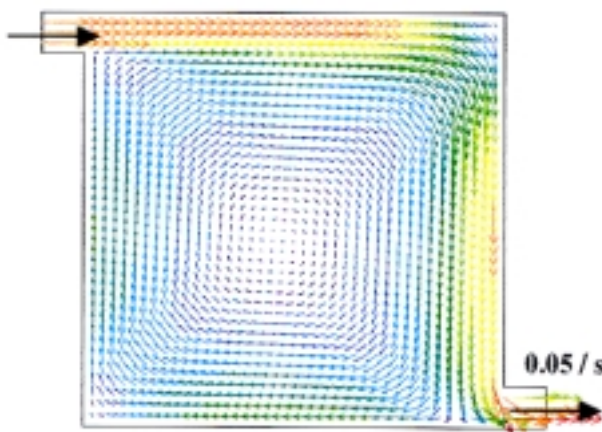


Figure 7: Velocity field in a 2-dimensional cross-section (2 m x 2 m area)

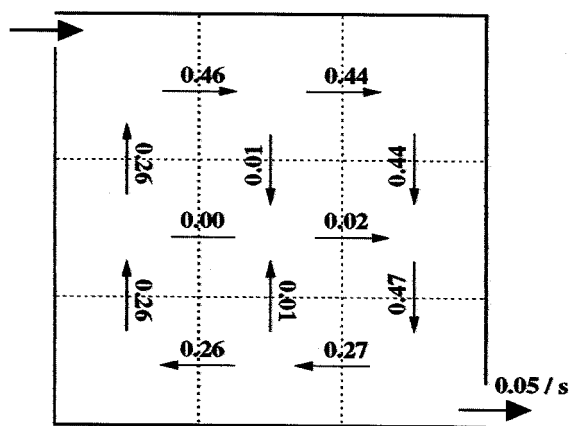


Figure 8: Air flow rates (m^3/s) between 9 compartments in a 2-dimensional cross-section (2 m x 2 m area)

Figure 8 shows the calculated transfer coefficients. They present a good agreement with the correct results by numerical simulation. The main flow within the room is also estimated correctly. There were some experiences made with several other conditions to test the method of compartmentalisation. In all cases the error level was beyond 10% [5].

In practical investigations such tests are not possible. But with consideration of the results of the theoretical examples the suitability of compartmentalisation was shown [6].

A practical example is shown in Figure 9. The picture on top shows a cross-section of a naturally ventilated stable for fattening pigs (the original is shown in Figure 1, right hand side). The air can only leave the stable through the slots or the side wall openings. The stable volume is divided into 21 compartments.

Using the decay method (second picture) one gets 21 average air change rates α which characterize the average air change rate at each measuring point. A comparison between the calculated air change rates is not allowed because the maximum (peak) of tracer concentration for every point is different in time! Only an average air change rate α for the whole stable and the whole time of measurement can be interpreted.

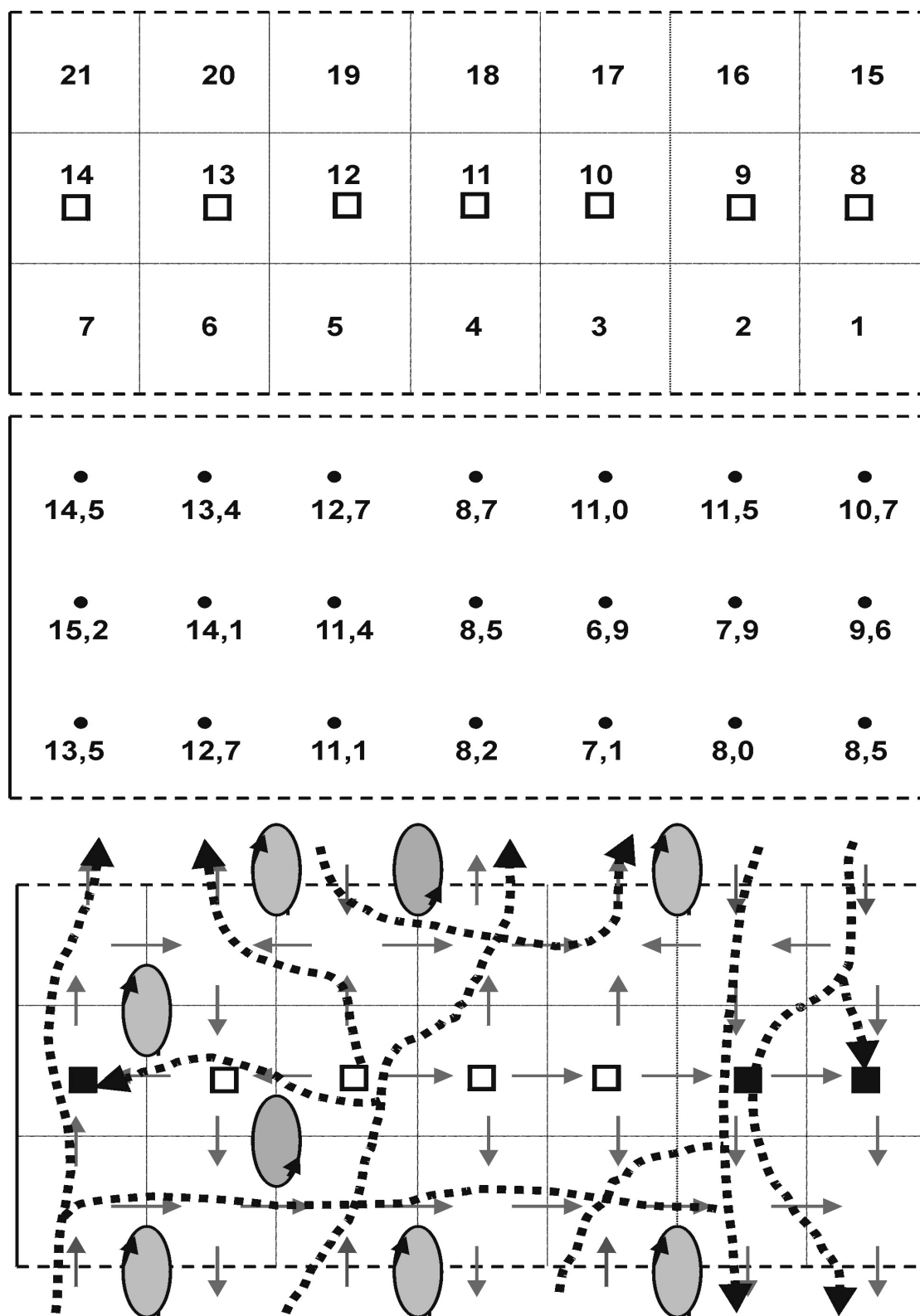


Figure 9: Practical using of compartmentalisation. At top there is a cross-section (21 compartments) of a natural ventilated stable. In the centre of each compartment is a measuring point for the tracer concentration. The analysis of the results is shown for the decay method (middle) and for the method of compartmentalisation (bottom).

Using the method of compartmentalisation (third picture) one gets 46 transfer coefficients which present the absolute air volume flow from one compartment into its neighbouring compartments. The plus and minus signs characterise the air flow direction. The sum of all outgoing transfer coefficients is the overall air volume flow of the stable.

Additionally it is now possible to get an imagination about the probable air flow pattern and eddies inside. So an opening can be identified as an inlet or an outlet. In comparison to the decay method the expressiveness of the method of compartmentalisation is fundamental higher.

6 Summary

Calculations of the airflow in stables with natural ventilation are uncertain because an open stable is directly dependent on the atmospheric conditions, i.e. wind velocity and wind direction. Analyses of simulation results which were determined using the tracer decay method show strong variations of the decay functions at different measuring points. Not only changing wind velocities but also the locations of the measurement points have a big influence on the decay behaviour. High wind velocities cause a faster dilution of the tracer concentration in the stable than small wind velocities. Through the various flow patterns in an open stable the decay behaviour becomes highly variable at each measuring point. Thus it is not possible to determine the air change rate based on decay functions or on an averaged air change coefficient.

With the help of compartmentalisation detailed results in calculation of emission mass flows of important gases like ammonia and odour are possible.

The first effect of the compartmentalisation is the calculation of absolute mass flows at different time steps. The second effect is the opportunity to get an estimation about the main air flow pattern inside a stable. So we can identify an exchange surface as an entry or an exit for a specific time step.

The method of compartmentalisation reduces the error in calculating of emission mass flows from natural ventilated stables and gives more accuracy in estimating the necessary distances between animal stables and their environment.

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