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Modelling Dust Emission from Fattening Pig Houses

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Original scientific paper

The objective of the study was to investigate the effect of changes in ventilation rate control settings on the dust emission from mechanically ventilated fattening pig houses. A mechanistic simulation model describing the dynamics of inside climate in intensive pig houses was combined with a dynamic data-based model that models the variation of dust concentration as a function of several input variables such as ventilation rate. By combining these two models, the effect of climate control strategies on the dust emission from the livestock houses can be simulated.

Key words: agriculture, dynamics, environmental engineering, modelling, living systems

1 INTRODUCTION

In intensive livestock houses the generation of dust is due to different sources: animal skin, hair, feathers, faeces, urine, feed and bedding materials. It is also well known that dust production increased with the number and weight of the animals [1]. Dust is made up of different size aerosol particles (with diameters ranging from few microns to hundreds of micron) and is divided into a »respirable fraction« and an »inhalable fraction«. The impacts of aerosols depend mainly on their physical size and on their biological and chemical composition. The respirable fraction of dust (particles less than 10 μm) can cause cough, soar throats and respiratory diseases among farmers [2]. It could also be dangerous for the animals because it carries micro-organisms and fungi [3]. Viruses carried into the air could cause infection in the neighbouring livestock building and could also create public health problems. Dust particles could also absorb irritant gases and odours.

The release and composition of particulate substances from livestock operations are influenced by the farm management and characteristics of the respective housing system, specified, for example, by feeding practices, bedding materials, fouled surfaces, number of animals, animal species, ventilation, and inside and outside climatic conditions [4, 5, 6]. The emission rate of PM10 particles (i.e., aerosols with a mass median diameter of $\leq$10 μm) differs seasonally and diurnally and is related to management aspects such as ventilation and working activity. In mechanically ventilated facilities, a high ventilation rate during summer results in a low indoor dust concentration but may increase dust emission rate [4, 7]. The influence of ventilation rate on dust emissions can be explained by the transport, settlement, and resuspension of airborne particles in relation to airflow patterns in the building. Gustafsson [1] reported that, depending on air velocity, less than 50% of the total amount of settled and airborne dust is ventilated to the outside. According to Haeussermann et al. [8], 64 and 96% of airborne particles measured indoors were transported to the outside in winter and summer, respectively (i.e. during measuring days with low and high ventilation rate). Keck et al. [9] found an increased impact of open yard exercises on the level of the absolute PM10 emission rate from pig husbandry during summer and a significant influence on PM10 emissions with increasing growth stage of growing-finishing pigs.

The objective of this paper was to model the dust concentrations in two different fattening pig houses and to simulate dust emissions as a function of outdoor conditions, indoor conditions and control strategies for both houses.

2 MATERIALS AND METHODS

2.1 Housing description and management

The experimental study was conducted in two pig houses in North Italy. The first swine house (Swine House type 1), was a mechanically ventilated building housing pigs from about 40 to 160 kg. The compartment was 16 m long and 12 m wide

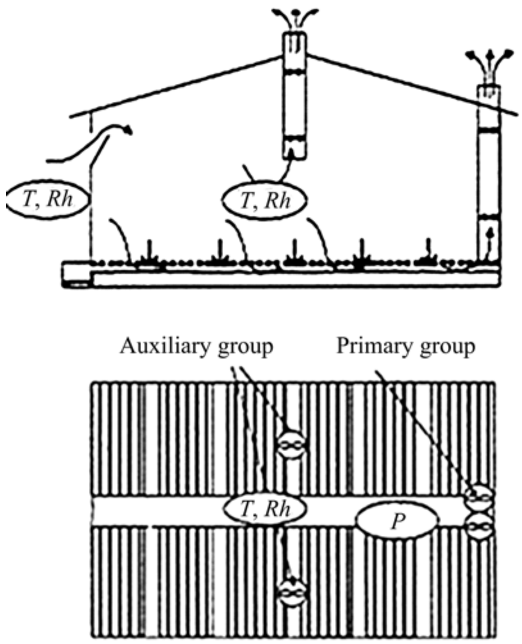

Fig. 1 Cross-section (top) and top view (bottom) of Swine House type 1. Sampling points and measured parameters are specified (P = particulate Matter; T = temperature; Rh = relative humidity)

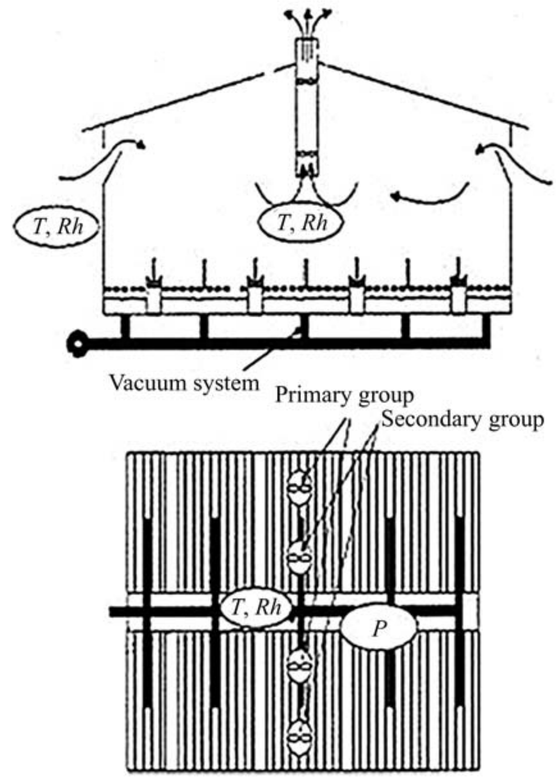

Fig. 2 Cross-section (top) and top view (bottom) of Swine House type 2. Sampling points and measured parameters are specified (P = particulate Matter; T = temperature; Rh = relative humidity)

with a maximum capacity of 210 pigs (0.9 m^2/head). The ventilation was realized with two groups of fans (each containing two axial fans) controlled by a digital controller using the feedback of a temperature sensor positioned in the compartment. Each exhaust chimney contained a fan and a free measuring turbine to measure the ventilation rate continuously. The first group of fans (primary group) took the air from under the fully slatted floors at the end at the room. The second group (auxiliary group) took the air 2 m above the fully slatted floors in the centre of the room as shown in Fig. 1. The primary group worked during the whole year while the auxiliary group worked only in the moments of greater necessity. The manure management system consisted of deep static pits.

The other pig house (Swine House type 2) was a compartment equipped with a system of quick and frequent removal of the manure called Vacuum System (Fig. 2). The compartment had a surface of 190 m^2 (15 × 12.5 m) and housed 232 pigs in two rows of 16 pens each. Also in this house, there were two groups of two axial fans acting as a primary and secondary group (see Fig. 2).

The fans took the air 2 meters above the fully slatted floors and they were positioned as shown in Fig. 2. In both swine houses, the animals were fed three times a day with automatic feeders from 4:15 to 6:45 a.m., from 10:45 a.m. to 1:15 p.m. and from 4:15 to 6:45 p.m.

Dust concentration (expressed in mg/m^3) was measured using the »Haz-Dust EPAM-5000«, which works on-line and gives the results in real--time. EPAM-5000 is a light scattering nephelometer and filter gravimetric air sampler. Size selective sampling was achieved by a single jet impactor for respirable dust (particles less than 10 μm). The accuracy of the dust sampling machine was ± .003 mg/m^3 (3 μg/m^3). In the pig houses the sampling location was along the central corridor, close to the fans. The dust concentration data were collected every 30 minutes. Temperature and relative humidity inside and outside the buildings were recorded by a data logger every hour. The accuracy of the measured temperature was ± 0,5 °C while the accuracy of the relative humidity measurement was ± 4% between 20% to 80% and ± 5% otherwise. Ventilation rate was measured with a freely rotating impeller (Fancom FMS). The sensors had a measuring range from 0 to 6000 m^3 h^{-1} in combination with pressure differences between 0 and 120

Pa. They were calibrated in a fan test rig that was built accordingly to the standards BS 848 and DIN 1952 and had an accuracy of 45 m^3 h^{-1}. Ventilation rate data were stored every hour. Data were measured in several seasons and several experiments per season were performed from July 2001 to April 2002 (Table 1).

Table 1 **Overview of the performed experiments**

Exp. No	Type of building	Date	Duration (hours)
1	HOUSE 1	July 01	50
2	HOUSE 1	Jan 02	70
3	HOUSE 1	Jan 02	24
4	HOUSE 1	Febr 02	78
5	HOUSE 1	Febr 02	42
6	HOUSE 1	April 02	68
7	HOUSE 1	April 02	72
8	HOUSE 1	April 02	68
9	HOUSE 1	April 02	90
10	HOUSE 2	July 01	62
11	HOUSE 2	Oct 01	44
12	HOUSE 2	Oct 01	47
13	HOUSE 2	Dec 01	37
14	HOUSE 2	March 02	64
15	HOUSE 2	March 02	47
16	HOUSE 2	April 02	92
17	HOUSE 2	April 02	54

2.2 Simulation models

In order to investigate the influence of ventilation rate on dust emission, two models were used. The first model, a mechanistic model, was used to analyze the dynamics of inside climate within the fattening pig houses. The different inputs of the model were: the number of animals, animal weight, date, characteristics of sensors, controller, ventilation system, heating system and building characteristics.

The model allowed simulating the resulting inside climate for varying outside conditions. The simulation model consisted of six different parts. These parts describe the different sub-systems of a ventilated pig house, such as the temperature controller, the heating system, the fan, the process of heat and mass exchange within the ventilated structure, the outdoor climatic data and the temperature sensor. Within each part, the dynamic actions between the inputs and the outputs were described by a set of differential equations, as formulated by Berckmans et al. [10]. This simulation model calculated the resulting indoor temperature and air humidity in a livestock building with a time step of 3 seconds over a time period of one year by using outdoor temperature and humidity data obtained from a dynamic reference year [11]. The simulation time step was chosen at 3 seconds, corresponding to the time constant of the fan. A number of input data, such as the time constants of the different sub-systems, the dimensions and thermal characteristics of the building structure, the simulation period, animal data and control settings allow simulating the different desired situations. The input parameters used in the model analysis are listed in Table 2 and Table 3. Since both swine houses were very similar in dimensions and material characteristics, we used the same building data in the model simulations.

In a next step, a data-based modelling technique was used to develop a second model. A black box

Table 2 **The climatic input parameters used in the model analyses (LU = Livestock Unit)**
(Building data: Total building surface wall: 160 m^2; Total building surface roof: 208 m^2; Total heat transfer coefficient: Kwall=1.1 $WK^{-1}m^{-2}$; Kroof=0.6 $WK^{-1}m^{-2}$; Proportional band = 3)

Time (Day)	T-opt (°C)	Vmin (m^3/h,LU)	Vmax (m^3/h,LU)
0	21	10	40
30	20	15	60
60	18	20	80
95	17	25	100
150	17	35	140

Table 3 **The animal input parameters used in the model analyses**

Time (Day)	Animal weight (kg)	Sensible heat (W/LU)	Latent heat (W/LU)
0	40	85	85
30	60	110	110
60	80	140	140
95	100	165	165
150	140	200	200

model was chosen to calculate the variation of the measured dust concentration as a function of the following variables: ventilation rate, inside air temperature, inside minus outside air temperature, absolute humidity and feeding time.

The model structure and model parameters were estimated through the collected data sets using a multi-input, single-output (MISO) transfer function (TF) model that can be written in the following form [12]:

$$y(k)=\sum_{i=1}^{m}\frac{B_i(z^{-1})}{A(z^{-1})}u_i(k-nk_i)+\xi(k) \qquad (1)$$

where $y(k)$ is the output (dust concentration) at time k; $u_i(k)$ is the i-th input (ventilation rate, inside air temperature, inside minus outside air temperature, absolute humidity and feeding time) at time k; nk_i are the time delays between the inputs and their first effects on the output; $A(z^{-1})$ is the denominator polynomial and equals to $1 + a_1 z^{-1}+a_2z^{-2}+...+a_{na}z^{-na}$; $B_i(z^{-1})$ are the numerator polynomials and equal to $b_{0i}+b_{1i}z^{-1}+b_{2i}z^{-2}+...+b_{nbi}z^{-nbi}$; a_j, b_j are the model parameters to be estimated; z^{-1} is the backward shift operator, $z^{-1}y(k)=y(k-1)$; n_a, n_{bi} are the orders of the respective polynomials; $\xi(k)$ is additive noise, a serially uncorrelated sequence of random variables with variance σ^2 that accounts for measurement noise, modelling errors, and effects of unmeasured inputs to the process (assumed to be a zero mean).

To identify the TF model order, the Young Identification Criterion (YIC) was used [13]; the time--invariant model parameters were estimated with an iterative instrumental variable algorithm (SRIV) [12, 14]. For every dataset a different TF model was estimated. The models were estimated based on the first 24 hours and validated on the whole dataset. For each of the two considered swine houses, the best model in terms of R^2 value was selected.

Based on the climate data of the dynamic reference year (cf. supra), the building data (Table 2), the animal data (Table 3) and the controller set points (Table 4), the indoor climate could be simulated using the mechanistic indoor climate model. The calculated values of the indoor climate (ventilation rate, inside air temperature, inside minus outside air temperature and absolute humidity) were used, together with the feeding times, as inputs to the data-based dust model for simulating the resulting dust concentrations. An overview of the coupling between the models is shown in Fig. 3. By

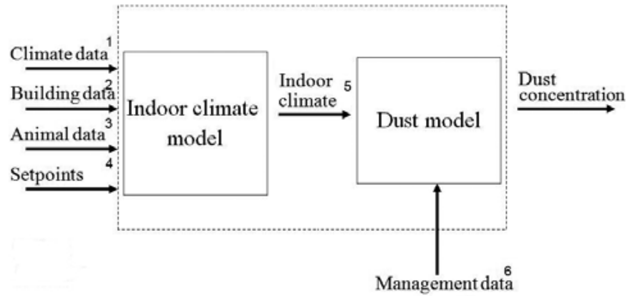

Fig. 3 Schematic overview of the coupling between the mechanistic indoor climate model and the data-based dust model: (1) Reference year of outside air temperature and relative humidity for the considered North Italian region; (2) Table 2; (3) Table 3; (4) Table 4; (5) Ventilation rate, inside air temperature, inside minus outside air temperature, absolute humidity; (6) Feeding time

combining a mechanistic model describing the indoor conditions from outdoor conditions and controller settings with a data-based model predicting dust concentration from indoor conditions and management information, it should be possible to evaluate dust emissions for the considered stables under different conditions of outdoor environment and control strategies without an excessive amount of experiments.

3 RESULTS AND DISCUSSION

Results showed that a first order model could be used to describe the dynamic response of dust to variations of the other measured variables. For Swine House I, the dust concentration could be modelled with a R^2 of 0.57. The following model parameter values (± standard deviation) were obtained: $a_1=-0.49$ (±0.12); b_{01} (ventilation rate) = $1.90\cdot10^{-6}$ ($\pm1.00\cdot10^{-6}$); b_{02} (inside temperature) = 0.014 (±0.003); b_{03} (inside temperature – outside temperature) =0.0085 (±0.0029); b_{04} (absolute humidity) =–7.8 (±5.6); b_{05} (feeding time) =–0.028 (±0.010). For Swine House II, the dust concentration could be modelled with a R^2 of 0.69. The following model parameter values were obtained: a_1 =–0.37 (±0.18); b_{01} (ventilation rate) $=1.11\cdot10^{-6}$ ($\pm4.99\cdot10^{-6}$); b_{02} (inside temperature) =0.0075 (±0.0032); b_{03} (inside temperature – outside temperature) = 0.0052 (±0.0027); b_{04} (absolute humidity) =–5.2 (±2.2); b_{05} (feeding time) =–0.012 (±0.005). The positive values for the b_{01} parameters (input ventilation rate) could possibly be explained by the fact that an increase in ventilation rate increased the air movement inside the pig houses and stirred up dust and kept much of it airborne, resulting in an increased dust concentration [2, 15].

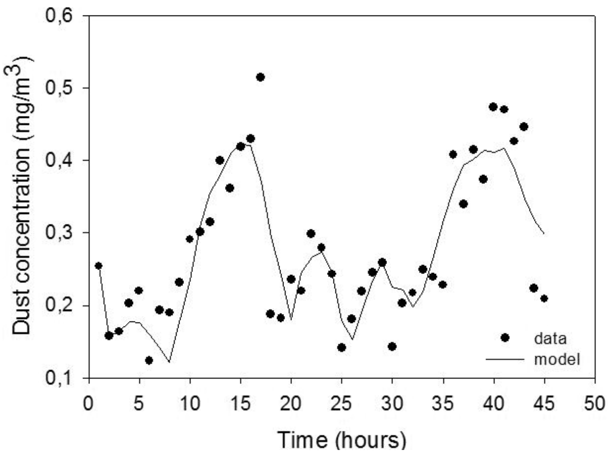

Fig. 4 Comparison of measured and modelled dust concentration for Swine House 2

Figure 4 shows an example of modelling results for Swine House I. The peaks in dust concentration at 15 and 40 h (during night time) can probably be explained by a falling air flow pattern caused by an increase in the temperature difference »inside temperature – outside temperature« and a lower ventilation flow rate.

By combining the mechanistic model with the data-based MISO dust model, different strategies to reduce the emission of dust have been analyzed. Three different ventilation control strategies have been compared for both pig houses. The first choice is the traditional way, the second strategy is with a different proportional band and the third strategy is with a different maximum ventilation rate.

Table 4 shows the corresponding values of the variables for strategy1, strategy 2 and strategy 3. The growth cycle, from 40 kg to 140 kg, took into account the period from January to the end of April 2002. Overall simulated mean respirable dust emission rates from pig buildings are shown in Table 5. The simulated dust emission values were lower than those reported in the literature for livestock building in Northern Europe. Takai et al. [4] reported a mean respirable dust emission rate of 59 mg/h, LU (LU, livestock unit). It could be expected that the ventilation control strategy with the highest proportional band gives the lowest ventilation rate since for a specific inside temperature above the set-point temperature the controller will give a lower ventilation rate. Dust emission is a direct result of ventilation rate times dust concentration of the exhaust air. In order to reduce the dust emission this is a good strategy. These simulations show how important the effect of the ventilation strategy could be.

Table 4 **Overview of the used values for the different climate control strategies (PB = proportional band)**

Strategy 1 (S1) – Strategy 2 (S2)					
S1, S2 Weight (kg)	S1, S2 V_{min} (m^3/h,LU)	S1, S2 V_{max} (m^3/h,LU)	S1, S2 T_{opt} (°C)	S1 PB (°C)	S2 PB (°C)
40	10	40	21	3	5
60	15	60	20	3	5
80	20	80	18	3	5
100	25	100	17	3	5
140	35	140	17	3	5

Strategy 1 (S1) – Strategy 3 (S3)					
S1, S3 Weight (kg)	S1, S3 V_{min} (m^3/h,LU)	S1 V_{max} (m^3/h,LU)	S3 V_{max} (m^3/h,LU)	S1, S3 T_{opt} (°C)	S1, S3 PB (°C)
40	10	40	60	21	3
60	15	60	80	20	3
80	20	80	100	18	3
100	25	100	140	17	3
140	35	140	180	17	3

Table 5 **Simulated dust emissions from January to April 2002 (LU, livestock unit)**

	Dust emission from Swine House 1 (mg/h, LU)	Dust emission from Swine House 2 (mg/h, LU)
Strategy 1	40.38 (100%)	14.92 (100%)
Strategy 2	38.77 (96%)	14.57 (97%)
Strategy 3	45.85 (113%)	15.95 (107%)

When comparing the results of ventilation strategies 3 and 2 (Table 5), it can be seen that in Swine House 1 differences in dust emission were 17% or 6 mg dust per LU and per hour. In Swine House 2 the reduction of dust emission between the considered ventilation strategies was 10%. Compared with the traditional control strategy (strategy1), the alternative strategies resulted in a calculated dust emission reduction of 4% and 3% for Swine House I and II respectively. Over the whole measuring period of 6 months this would result for Swine House 1 in an important total difference of dust emission.

However when reducing the ventilation rate in a fattening pig house, it might be expected that there is an increase of the inside temperature. Due to the higher inside temperature, the NH_3 emission will increase which is a negative effect. Therefore, the effect of ventilation rate on dust emission in combination with the effect on NH_3 emissions has to be analysed in future.

Another point is that the ventilation strategy has different effects in the two swine houses. Since they have different ventilation systems there will be corresponding differences in the resulting air flow patterns in both the buildings. Next to this it might be expected that there are differences in the dust concentrations in the buildings. The black box model constructed for each building with the measured data is taking these differences into account and consequently we get different effects of ventilation strategies in both buildings (up to 17% difference in dust emission between the different strategies in one building).

4 CONCLUSIONS

Based on the simulation results, the following conclusions can be summarized: 1) The emission of dust is affected by housing type. There are significant differences among the two livestock buildings: mean respirable dust emission is higher in swine type 1 than swine type 2. This can be explained by the differences in the ventilation systems with corresponding expected differences in air flow patterns and inside dust concentrations; 2) Dust emission from swine type 1, equipped with deep static pits, is 2.5 times higher than swine type 2 equipped with a system of quick and frequent removal of the manure; 3) Comparing three different strategies (the traditional way, the strategy with a different proportional band and the strategy with a different maximum ventilation rate) shows that an appropriate choice of ventilation strategy can have an important effect on dust emission. An appropriate choice of the proportional band of the ventilation rate can have an hourly reduction of the dust emission up to 4% compared to the traditional control strategy in the considered buildings; 4) The reduction of the ventilation rate is a good strategy to reduce the dust concentration but will increase the average inside temperature. Consequently it might be expected that the NH_3 emission might increase due to the effect of temperature on NH_3 emission. The effect of ventilation strategy on the combination of dust emission and NH_3 emission should be studied in future.

ACKNOWLEDGEMENTS

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Modeliranje emisije prašine u nastambama za tov svinja. Cilj je ove studije istražiti učinak promjena postavnih veličina intenziteta ventilacije na emisiju prašine kod mehanički ventiliranih nastamba za tov svinja. Simulacijski model mehaničkoga dijela opisuje dinamiku unutar klimata u intenzivno pogonjenim nastambama te se kombinira s dinamički podatkovno zasnovanim modelom koji modelira varijaciju koncentracije prašine kao funkciju nekoliko ulaznih varijabla poput brzine prozračivanja. Kombinacijom se tih dvaju modela može simulirati učinak strategije vođenja na emisiju prašine u životinjskim nastambama.

Ključne riječi: agronomija, dinamika, inženjerstvo okoliša, modeliranje, živi sustavi

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