Measurement and Modelling of Circumstances in Animal Houses: What, Why and How

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Abstract. The indoor air of the animal house has to be of such quality that the animal, the human being and the building should feel well. It means suitable temperature without moisture and gas, microbe and dust contents which should be low enough. The objective of our studies is to create general physical-chemical models for the ventilation and temperature of animal houses as the function of factors which affect micro climate (temperature, moisture, gases, dust, microbes, mould) and the heat balance of the animals. The optimal climate given by the models is achieved by the right ventilation. A system which is automatic or gives alarms and can be used to carry out the optimum conditions of the animal buildings in as stable a way as possible is needed. For this purpose reasonable and reliable sensors which measure the right factors are needed. So the results of sensors can be used for model based control of the ventilation in which case one can switch to the modelling adjustment in which more quantities can be simultaneously used and in such a way the quality of the indoor air of animal houses can be improved by the adjustment of only one quantity (temperature or moisture or carbon dioxide or other gas).

Key words: Ventilation, modelling, animal houses, sensors, balance

INTRODUCTION

Ventilation is needed in animal buildings for removing harmful gases in order to ensure acceptable indoor microclimate. Microclimate parameters such as the concentration of gases, temperature, air velocity, dust and humidity affect the welfare of animals, humans and buildings themselves. On the other hand, ventilation rates are required to estimate the amount of gases emitted from animal houses. The rate of production (P in m^3 h^{-1}) of a specific gas in an animal building is given by the mass balance:

$$P = q_V \left(C_{in} - C_{out} \right) = q_V \; \Delta C \tag{1}$$

where q_V (m^3 h^{-1}) is the ventilation rate, and C_{in} (m^3 m^{-3}) and C_{out} (m^3 m^{-3}) are the concentrations of the gas inside and outside the animal building, respectively. If P is known, ventilation rate may be calculated from Eq. 1. Suitable gases the production of which P is known are CO_2, water vapour and methane.

Animal buildings may either be mechanically or naturally ventilated, or a combination of these two. There may also be possibilities to regulate the rate of ventilation in the buildings by adjusting fan flow rates (mechanically ventilated), closing windows or rolling up curtain walls (naturally-ventilated curtain-wall barns). Air exchange in mechanically ventilated buildings is usually done by fans, and the ventilation rates are then:

$$q_V = v \cdot A \tag{2}$$

where A (m^2) is the cross-sectional area of the fan and v (m s^{-1}) is the average air flow through the fan.

To evaluate their practical usefulness, four methods of estimating ventilation in dairy buildings were compared by Teye & Hautala (2007): heat balance, moisture balance, carbon dioxide balance and direct air flow measurements in a naturally ventilated dairy barn. Rather big differences were observed.

In this paper, first of all, we express the theoretical considerations concerning ventilation in section 2. Various balances together with recommendations for the microclimate in cow houses are used to calculate the minimum ventilation per cow. Ammonia emission model is presented that gives ammonia emission as a factor of T, RH, v and pH. Thus, the microclimate in cow houses can easily be calculated and automatic ventilation should function. In section 3, we describe the apparatus that can be used for the automatic measurement of microclimate in animal buildings. In section 4, we give some results of the measurements performed in cow houses, piggery and poultry houses. In section 5, we describe what is most important in determining the ventilation in animal houses in various circumstances.

THEORY

Carbon dioxide and methane balance

Assuming ideal mixing, the ventilation rate, q_V of a animal building (as used in Equation 1) can be estimated by measuring the rate of production, P of a tracer gas in the building and the differences in the tracer gas' concentration in and outside the building, ΔC as:

$$q_V = \frac{P}{\Delta C} \tag{3}$$

The gas involved (tracer gas) could be an artificially produced gas if the rate of production is known. Methane (CH_4) and carbon dioxide (CO_2) in solid floor dairy buildings with regular manure removal are considered to be produced mainly from the dairy animals' metabolism and therefore could be used as a tracer gas. If the production of CO_2 and CH_4 from other sources in a dairy barn is negligible, then 330 g h^{-1} of CO_2 per cow (CIGR, 1999), and 10 g h^{-1} of CH_4 per cow is produced in a dairy building (Amon et al., 2001; Hindrichsen et al., 2005; Johnson & Johnson., 1995; Jungbluth et al., 2001). Measurements have indicated (Teye and Hautala, 2008) that less than 10% of the total emission of CH_4 and CO_2 emerge from dairy building floors, confirming the assumption of cows being the main source of production to be fairly good.

Estimated from Equation (3), the minimum ventilation rate per cow to keep CO_2 concentrations below recommended harmful limits (3,000 ppm according to CIGR, 1984) is 100 m^3 h^{-1}. For a typical dairy building with 100 m^3 space per cow, the minimum exchange rate of air is about once an hour to keep CO_2 concentration below the recommended harmful limit.

Water balance

The amount of water or moisture produced per cow is well documented (CIGR, 1984). In dairy buildings, ventilation rate is calculated from moisture balance as:

$$q_V = \frac{P_{H_2O}}{\left(C_g - C_{out}\right)} = \frac{P_{H_2O}}{\rho_{air}\left(x_{in} - x_{out}\right)} = \frac{P_{H_2O}}{\rho_{air} \cdot \Delta x} \qquad (4)$$

where x is the water content (kg kg^{-1}), ρ_{air} is the air density (kg m^{-3}), P_{H_2O} is the total production of water vapour, i.e. from cows and from the building floors.

Similarly as in the section discussing CO_2 and CH_4 balances, the minimum ventilation using water balance can be estimated based on Equation (4). The problems of moisture in dairy buildings occur during winter when relative humidity (RH) ranges between 80 and 100%. During a winter with inside and outside air RH of 80 and 100% respectively, if the inside and outside temperatures are 10 and 0° C respectively, Δx will be 0.003. Furthermore, if the inside and outside temperatures are 0 and -10° C respectively, Δx will be 0.002, and if the inside and outside temperatures are 0 and -20° *C* respectively, Δx will be 0.003. Hence, if winter average water production, P_{H_2O} is 500 g h^{-1} per cow (CIGR, 1984), then the minimum ventilation rates according to equation (4) will be between 150 and 250 m^3 h^{-1} per cow, assuming the water emission from other sources to be negligible.

Heat balance

Ventilation according to heat balance is expressed as:

$$q_V = \frac{P_{heat} - P_{loss}}{\rho\ c_s\left(T_{in} - T_{out}\right)} \qquad (5)$$

where P_{heat} is the heat produced indoors by animals, heat system, illumination etc. (W), P_{loss} is the heat lost through the floor, walls and ceilings (kW), T_{out} is the temperature of the outdoor air (°C), c_s is the specific heat of air (J kg^{-1} K^{-1}) and ρ is the air density (kg m^{-3}).

The required ventilation rate for a fully insulated building (no losses, no heating) estimated from Equation (5) is 360 m^3 h^{-1} per cow if the difference between inside and outside temperature is 10° C, and the heat production per cow is 1 kW (CIGR, 1984). In winter ventilation is minimized in order to keep temperature indoors as high as possible. Neglecting heat losses, even temperature difference 40° C allows ventilation to be 100 m^3 h^{-1} per cow. Thus, a suitably insulated cow house does not need a heating system.

Comparing the ventilation rates from Equations (3), (4) and (5), it can be deduced that, to ensure safe and comfortable microclimates for human dairy workers (indoor temperature above zero and CO_2 less than 3,000 ppm), the minimum ventilation rate should be 100 m^3 h^{-1} per cow, i.e. an exchange rate of about once an hour.

Ammonia emission model

The NH_3 emission from manure can be separated into different processes. NH_3 molecules are first created in the manure in various chemical and microbiological processes. Then the molecules diffuse to the surface of the manure. From the surface they further diffuse in the air through the laminar boundary layer and finally by turbulent convective motion into all parts of the building. Turbulent motion is assumed to be fast enough to yield space independent concentrations. This is the so-called ideal mixing model.

NH_3 emission rate is theoretically modelled using information from literature. First, the surface concentration of NH_3 is calculated using equations adopted from Zhao and Chen (2003): the amount of NH_3 dissociation in the manure, the fraction of NH_4-N concentration in the total ammoniacal nitrogen C_{TAN} (kg m^{-3}) and the ratio of the NH_3 concentration at the manure side of the interface between the manure and the air and the NH_3 concentration at the air side of the interface between the liquid manure and the air. This comes from chemistry and microbiology. Then physics, i.e. Fick's law of diffusion and boundary layer theory are used for mass flux calculation from the manure surface. The final approximate equation (deviates less than 50% from exact calculations) is (Hautala, 2007; Teye and Hautala, 2008)

$$emission\ flux\,(g\ m^{-2}\ h^{-1}) = 0.02 \cdot 10^{T(^oC)/20+pH-8} \cdot C_{TAN}(kg\ m^{-3})\,/\,\delta(mm) \quad (6)$$

where δ (in mm) is the thickness of the laminar boundary air layer and presents the physics part of the equation in addition to the fact that emission rate is strictly proportional to emitting area, when diffusion plays a role. δ varies from 2 to 20 mm depending on the wind. 20 mm calm, 2 mm strong wind. If necessary, δ may be measured as explained by Teye and Hautala (2010). Neither of these assumptions is strictly valid in practical cases. Equation (6) is valid for any cover. For a porous cover, δ is the thickness of the cover. For liquid or solid cover, flux should be divided by at least 10^4 since diffusion coefficient is so much smaller in a liquid than in the air. If the manure is put into soil, δ is the relevant depth of soil above the NH_3 level. This is so according to the rules of physics.

METHODS

The stationary telemetry air quality monitoring and measurement system consisted of a central measurement unit and additional wired sensors located at different positions in and outside the animal buildings (Teye et al., 2009). The central measurement unit for telemetric transmission of air quality data was a 1m by 1m flat wooden board on which a General Packet Radio Service (GPRS) transmitter (a-Lab Oy's AWS-Core) and a set of air quality sensors were fitted. The sensors attached to the board of the central measurement unit continuously measured air temperature, manure temperature (infrared), radiation, relative humidity, air velocity, ammonia, and carbon dioxide concentrations in the building.

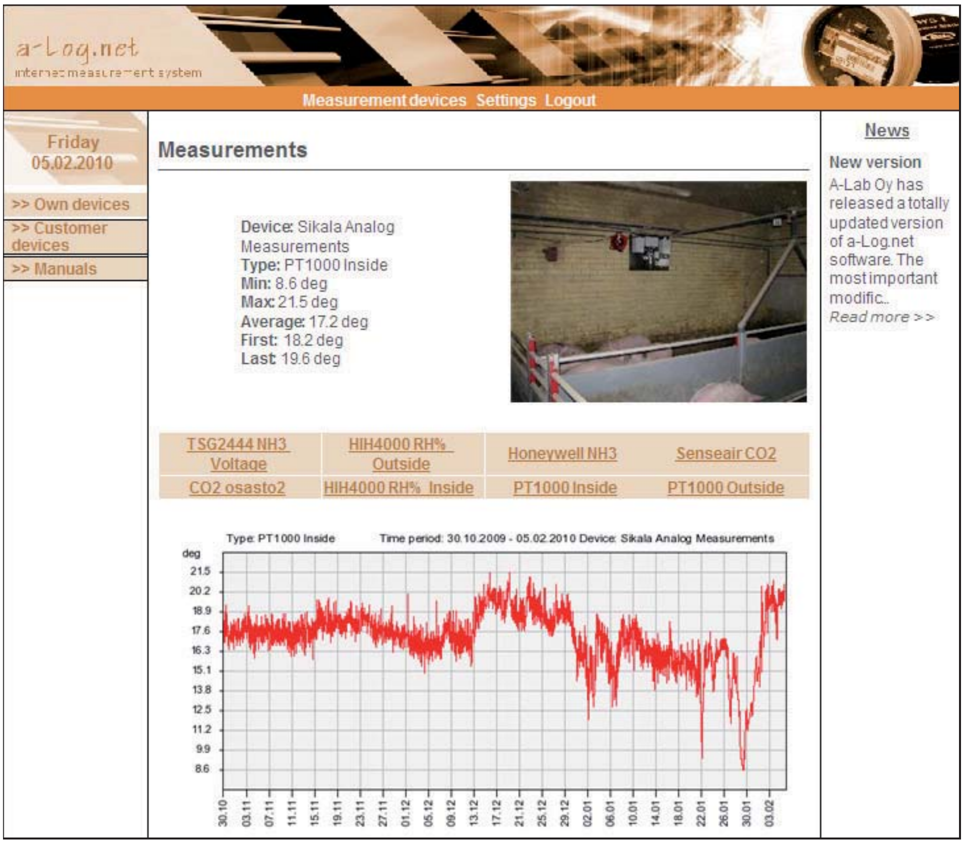

Fig. 1. An internet page showing the implementation of wireless data transmission of indoor air in piggery. The equipment is seen hanging on the wall in the inset.

All wiring connections and sensitive electronics were shielded from dust and moisture. Measurements were performed at a 30-minute interval and the data was sent through GPRS to a database server to be viewed or downloaded over a World Wide Web (WWW) interface. Fig. 1. shows a preview of the measurements taken with the wireless measurement system as viewed from the internet.

RESULTS

In Fig. 2 the CO_2 concentrations in two different kinds of dairy barns are shown. In the semi-insulated dairy barn the CO_2 concentrations are much higher in winter than in the uninsulated one. The farmer has obviously closed the curtains to keep the air warm inside. In the uninsulated barn the concentration stays all year round at a low level, 500-1,000 ppm.

Figs. 3-5 show measurements in other animal buildings. It can be clearly seen that the concentrations in winter are most of the time above the recommendations (3,000 ppm) but also that there is strong variation as a function of animal size (broilers) and time of the day.

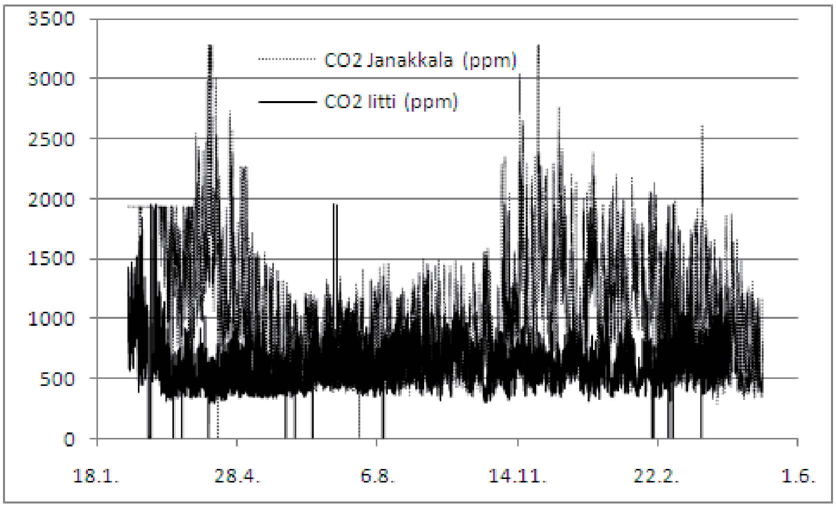

Fig. 2. CO_2 concentrations in a semi-insulated (Janakkala) and an uninsulated (Iitti) dairy barn.

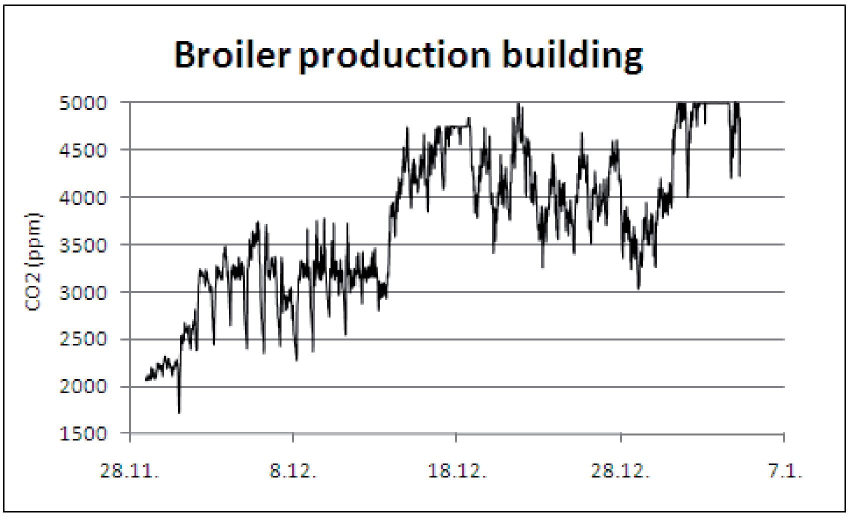

Fig. 3. CO_2- concentration development during the growth of broilers.

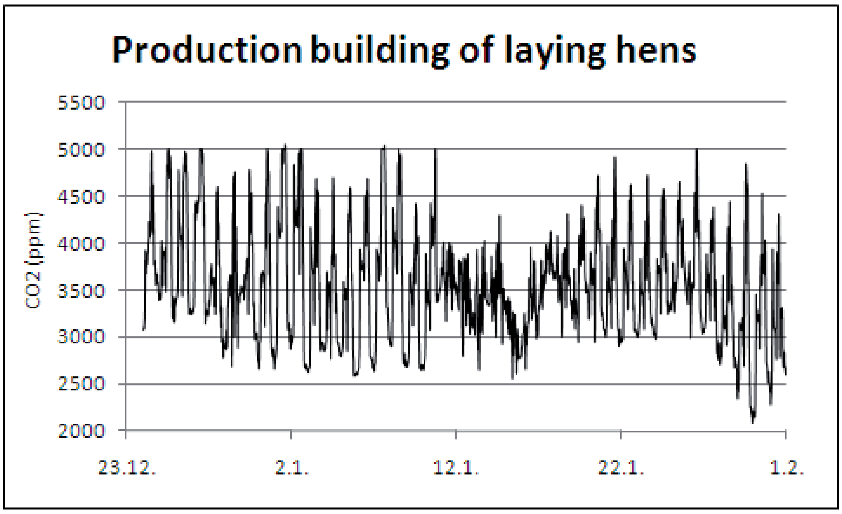

Fig. 4. Daily variation of CO_2-concentration in a hen house.

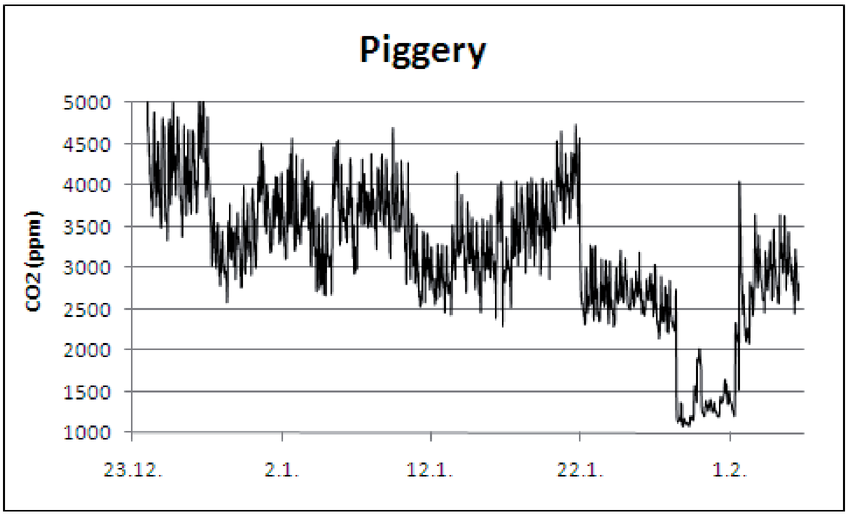

Fig. 5. CO_2-concentration in a piggery. The pigs were removed 26.1 and new ones came 2.2.

DISCUSSION AND CONCLUSIONS

Methods given in section 2 give adequate theoretical background concerning T, RH, CO_2, CH_4 and NH_3 in most situations, especially in dairy barns, where no heating is needed, if the house is suitably insulated. Ventilation can adequately be regulated by CO_2-sensors, which are cheap and have turned out to be reliable. Poultry houses as well as piggeries are different. They need heating in winter and this may be costly. One may roughly calculate the cost e.g. in a piggery. The ventilation per pig must be about 20 m^3 h^{-1}. If the outdoor temperature is -20^o C and indoor +10^o C, heating of this air in one day needs energy

$$q_V \text{ time } \rho\ c_s\ \Delta T = 20\ m^3\ h^{-1}\ 24\ h\ 1\ kg\ m^{-3}\ 30\ K\ 1\ k\ J\ kg\ K = 14\ MJ = 4\ kWh.$$

If the weight increases 1 kg day^{-1}, the cost is 40 cents pig kg in Finland. This noticeable cost means that the regulation of ventilation is of utter importance, as well as it would be very useful to know the lowest temperature the pig can stand in various conditions, e.g. in case the floor is heated. A simple heat balance model that gives the lower critical temperature is given in Hautala et al. (2008). We clearly need reliable sensors to regulate ventilation. When the activity in the night time is small, water evaporation and CO_2 emission are smaller and less ventilation is needed. Probably a good combination of sensors for automatic control of ventilation is T and CO_2. Both are cheap and reliable.

We have totally neglected here dust and microbes. Our preliminary measurements in Finland indicate very alarming concentrations of both dust and microbes especially in broiler and hen houses. The primary reason evidently is the use of peat.

REFERENCES

Amon, B., Amon, T., Boxberger, J. & Alt, C. 2001. Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall, *Nutrient Cycling in Agroecosystems.* **60**, 103-113.

CIGR. 1984. Climatisation of animal houses, Report of working group on climatisation of animal houses, International Commission of Agricultural Engineering (CIGR), Scotland.

CIGR. 1999. CIGR Handbook of Agricultural Engineering, Volume II edn. Bartali E H, Wheaton F W and Singh S (eds.). Published by American Society of Agricultural Engineers, USA, pp395.

Hautala, M., Mäkelä, M., Pastell, M., Raussi, S., Hänninen, L. & Saloniemi, H. 2008. Upper and lower critical temperatures for cattle, AgEng2008 International conference on agricultural engineering: conference proceedings CD. – Athens AgEng2008 P-146, 9 s.

Hautala, M. 2007. NH_3 emission from manure: physicist's view. *Ammonia emissions in Agriculture*, Wageningen, p. 277-278.

Hindrichsen, I.K., Wettstein, H.R., Machmuller, A., Jorg, B. & Kreuzer, M. 2005. Effect of the carbohydrate composition of feed concentratates on methane emission from dairy cows and their slurry, *Environmental monitoring and assessment.* **107**, 329-350.

Johnson, K. A. & Johnson, D. E. 1995. Methane emissions from cattle, *Journal of animal science.* **73**, 2483-2492.

Jungbluth, T., Hartung, E. & Brose, G. 2001. Greenhouse gas emissions from animal houses and manure stores, *Nutrient Cycling in Agroecosystems.* **60**, 133-145.

Teye, F. K. & Hautala, M. 2007. Measuring ventilation rates in dairy buildings, *Journal of Ventilation*, **6**, 247-256.

Teye F. K. & Hautala M. 2008. Adaptation of ammonia volatilazation model for naturally ventilated dairy buildings, *Atmospheric Environment*, **42**(18), 4345-4354.

Teye F. K., Alkkionmäki, E., Simojoki, A., Pastell, M., Hautala, M. & Ahokas, J. 2009. Instrumentation, measurement and performance of three air quality measurement systems for dairy buildings, *Applied Engineering in Agriculture, ASABE,* **25**(2), 247-256

Teye, F. K. & Hautala, M. 2010. A comparative assessment of four methods for estimating ammonia emissions at microclimatic locations in a dairy building, *Int. J. of Biometeorology,* **54**, 63-74.

Zhao, B. & Chen, S. 2003. Ammonia volatilization from dairy manure under anaerobic and aerated conditions at different temperatures. ASAE Annual International Meeting. ASAE Paper Number 034148.