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Study of the Environmental Control of Sow Farrowing Rooms by Means of Dynamic Simulation

Enrico Fabrizio[1] Gianfranco Airoldi[2] and Roberto Chiabrando[2]

Abstract. While there has been a great reduction of the energy demand of civil buildings in recent years, the energy demand for the environmental control of livestock buildings is still high, due to high outdoor air changes. In a livestock building, a compromise between different requirements (reducing the heating energy in winter season, avoiding heat stress for animals in summer season, controlling the relative humidity, controlling ammonia and hydrogen sulfide concentrations) has to be done and contributes to complicate the design of the structures and the operation of the ventilation system. Moreover, depending on the animal species, ages and type of housing, the environmental control requirements change considerably. In the present work, dynamic building simulation is applied to a portion of a swine unit, in particular the sow farrowing room and weaned pigs nursery, where the effects of some important construction and HVAC system choices that influence the temperature and humidity conditions and the sow thermal comfort were investigated. The results show that the use of variable flow rate fans, able to implement in the summer season free cooling with the outside air, coupled to a building structure sufficiently massive to exploit the effect of free cooling, is surely promising. The thermal insulation is useful to reduce the energy consumption for heating in winter and does not affect the summer overheating.

Keywords: free cooling · swine farm · sow farrowing room · dynamic simulation

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1 Introduction

The numerical simulation of the building energy performance, in particular the dynamic building simulation, that is able to verify the energy performance of a building under the operating conditions and evaluate the effects of various design choices, is widely used in research works and in many professional applications in the civil sector. This is due to many factors, including the spread of computer codes increasingly detailed and freely available online, the study of simulation models of building components and innovative plant designs, the need to meet long-term energy performance requirements imposed by law or such as to give a score within the tools for sustainable building. Conversely, the use of dynamic simulation appears limited as regards the manufacturing buildings such as livestock and greenhouse buildings. In such cases, in which the use of the active indoor climate control is limited for reasons of technological and economic opportunities, the use of instruments which enable the evaluation of passive climate control strategies (linked to the building structure) such as the dynamic energy simulation would be particularly useful. For livestock buildings, usually self-made calculation tools are employed, see for example [1] and [2] in case of swine buildings. In the present work, the dynamic building simulation was applied to a sow farrowing room and the effects of some important construction and HVAC system choices were investigated.

2 Materials and methods

2.1 The calculation tool

The dynamic simulation of the sow farrowing room was conducted by means of the EnergyPlus software (www.apps1.eere.energy. gov/buildings/energyplus), one of the most recent and updated software tool for the simulation of the energy performance of the building and of the primary and secondary systems, widely used at international level. Even though the software was not designed for particular buildings such as livestock buildings and greenhouses, this simulation was conducted exploiting the capabilities of the software and adopting the pertinent assumptions. An example of application of EnergyPlus for the study of the thermal behaviour of a greenhouse can be found in [3].
In EnergyPlus the thermal load is determined by computing the Air Heat Balance on a time step of 1/6 of an hour. The thermal conduction through heat transfer sur-

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faces is computed by menas of the CTFseries method. The radiative heat exchange is computed in detail, distinguishing between the short-wave and long-wave radiation. Due to the fact that the indoor humidity was also studied in the simulation, the effect of the vapour inertia of the indoor surfaces was taken into account by means of the EMPD (effective moisture penetration depth) model.

2.2 The reference building

A reference building consisting of a sow farrowing room in a swine farm, equipped with forced ventilation, for a total of 10 sow and 84 m^2 (Figure 1 left) was assumed. The dimensions are reported in Figure 1 right; the room is configured as a portion of a building whose longitudinal axis is oriented along the direction east-west; the side walls are therefore adiabatic. The pent roof is oriented to the south. In the initial configuration, the constructions are made of gas concrete (30 cm) for the external walls, insulated plate (10 cm) for the roof and polycarbonate single pane windows for the openings. The floor is a plastic grid that separates the indoor environment from the sewage pit, that is 90 cm deep and made of concrete. There is an air heating HVAC. The mitigation of the thermal conditions during the summer is made by increasing the outside air flow rate (free cooling).

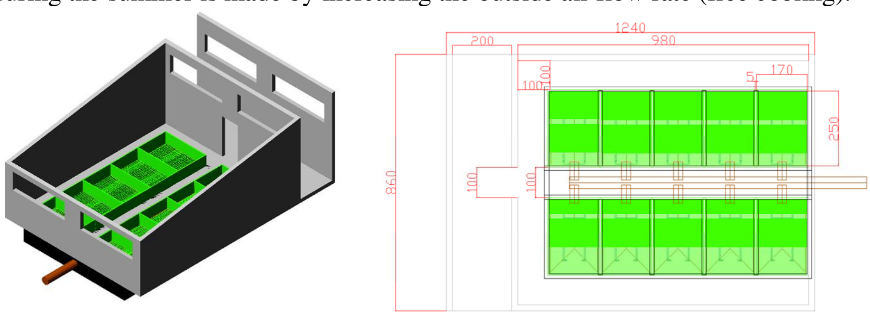

Fig. 1. View and dimensions of the sow farrowing room under consideration

2.3 Boundary conditions

The use of the sow farrowing room is as follows:

- 7 days: presence of the pregnant sows in each pen;
- 28 days: presence of the lactating sows and 11 piglets for each sow/pen;
- 7 days: cleaning and disinfection.

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The above cycle is repeated 8.7 times during a calendar year. The sensible and latent heat loads due to the presence of the animals were estimated on the basis of CIGR values [4], assuming a body weight of pregnant and lactating sow of 200 kg and a variable weight of piglet from 1.2 kg – at birth – to 8 kg, with a daily average increase of 240 g. To evaluate the total load and split it between sensible and latent, a winter season, a summer season and an intermediate season were identified. The profiles of the sensible and latent heat loads due to animals were normalized to a maximum value of 6190 W for the sensible load and of 6500 W for the latent load.

The contribution to the energy balance due to the manure was estimated from the CIGR data of daily defecation [4], by evaluating the accumulated liquid manure and the evaporation, proportionarily to the difference between the saturation vapor pressure at the surface temperature of the floor and the vapor pressure of the indoor air, as reported in [5] and in the references cited there. In heating mode, a set point temperature of 18 °C was fixed, while for the piglets heating at higher temperatures in the first weeks of life, radiative lamps were considered. In summer conditions, the internal temperature of activation of the free cooling was set to 26 °C. This is the temperature above which the outdoor air flow rate is increased, provided that the dry bulb temperature is sufficiently lower, to maintain the indoor environment to 26 °C (to this regard see the following graphs of Figure 4). On the basis of the maximum production of carbon (1647 l/h) the minimum ventilation air flow rate was estimated as

$$\dot{V} = \frac{\dot{q}_{CO_2}}{C_{in} - C_{out}} = \frac{1647 \cdot 10^{-3}}{0{,}032} = 514{,}79 \text{ m}^3/\text{h} = 0{,}143 \text{ m}^3/\text{s} \qquad (1)$$

The maximum ventilation flow rate was estimated on the basis of the summer thermal load of the building and was fixed equal to 10 times the minimum value. Different simulations were conducted adopting a two-speed fan or a variable flow fan.

The variables that were analyzed are the followings:

- heating energy requirement (set point 18 °C);
- electricity requirement for air circulation (heating and ventilation in winter, and ventilation with optional free cooling in summer);
- sum of the two previous quantities in terms of primary energy by adopting a weighting factor equal to 1 for the thermal energy and 2.17 for the electricity;
- index of overheating of the building during the summer. In the absence of a mechanical control of the internal temperature, this index is a parameter for the evaluation of the different design solutions and was defined as

$$I_s = \sum_j \left(t_{i,j} - t_R\right) = \sum_j \left(t_{i,j} - 26\right) \qquad [°\text{C} \cdot \text{h}] \qquad (2)$$

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that is the sum of the positive differences between the hourly indoor air temperature and a reference temperature fixed at 26 °C (equal to the temperature of the activation of the free cooling). This sum represents the time during which the indoor air temperature exceeds the limit temperature, weighted for the entity of the deviation.

The weather conditions refer to the IWEC file of the Torino location (northwest of Italy). The running period is one year. The following cases were analyzed:
case 1) building construction as in § 2.2, two flow steps fan (step 1: 0,715 m^3/s; step 2: 1,43 m^3/s) with flow regulation with deflector;
case 2) building construction as in § 2.2, variable flow fan in all outside air, controllihg the flow from a minimum of 0,143 m^3/s to a maximum of 1,43 m^3/s;
cases 2.1-2.2-2.3) as case 2) with an increase of the thermal insulation (10 cm, 15 cm, 20 cm) of the roof;
case 3) concrete walls, for both heat transfer and adiabatic surfaces, (20 cm, 1200 kg/m^3 specific mass, 0,39 W/mK thermal conductance), ventilation as in case 2);
cases 3.1-3.2-3.3-3.4-3.5) as case 3) with thermal insulation respectively of 5 cm, 10 cm, 15 cm, 20 cm, 25 cm;
case 4) concrete walls with low insulation – as in case 3.1) – and roof insulated as in case 2.2).

Finally, the hourly electricity production of a monocristalline PV plant (design efficiency of modules of 18%) on the on the south-oriented pent roof was calculated assuming a consumption for the fans and the selling of the exceeding electricity.

3. Results

In Figures 2 and 3 the time profiles of the average indoor air temperature and the outside air ventilation flow rate are represented; for clarity the trend of the outdoor air temperature is also shown in the background. In case 1), in which the ventilation flow rate is equal to only two values, we see that it is necessary to activate the higher ventilation flow rate at the beginning of May, and maintain it until mid-September. The energy consumption of this and the following configurations are reported in Table 1. In the graph of Figure 3 it can be noted that with the variable flow fan it is possible to reduce to the minimum the flow rate during the winter period, with a consequent reduction of electricity consumption for the air movement (from 6478 kWh to 3757 kWh) while the maximum flow rate is achieved when the free cooling is needed. This solution is instead comparable with that of case 1) for the other quantities.

To better understand the operation of the free cooling, in Figure 4 weekly trends of the indoor parameters in two periods of activation of the free cooling in different modes are shown. In both cases the periods of activation for the free

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cooling can be recognized by the rising of the outside air flow rate above the lower limit (fuchsia curve). In the week on the left, with outside temperatures lower than the one that is fixed as internal set point (26 °C), free cooling is active during the day, and it is almost always possible to maintain the indoor temperature at 26 °C (horizontal sections of the blue curve); at night vice versa there is a drop in the indoor temperature due to the base ventilation.

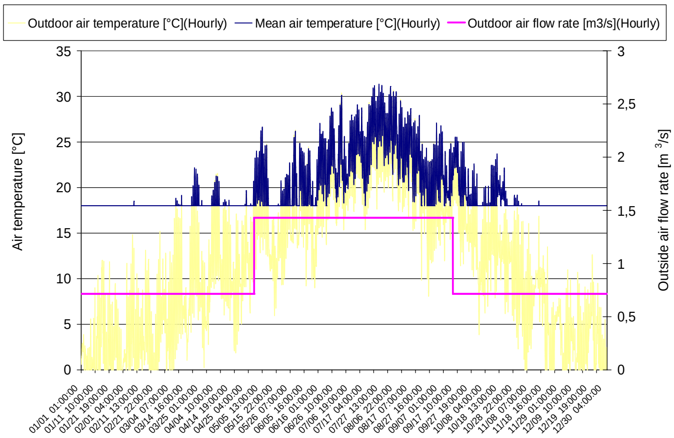

Fig. 2 Hourly profiles of indoor air temperature and flow rate for case 1

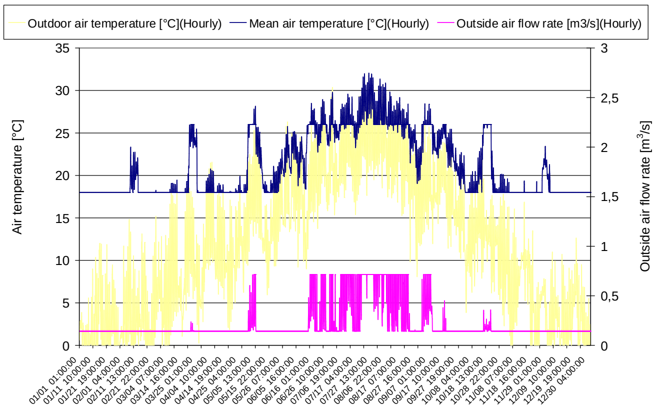

Fig. 3 Hourly profiles of indoor air temperature and flow rate for case 2

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Table 1 Summary of the results for the main case studies (sensitivity analysis on the thermal insulation are omitted)

	Case 1)	Case 2)	Case 3)	Case 4)
Fan	Constant flow (2 steps)	Variable flow	Variable flow	Variable flow
Free cooling	no	yes	yes	yes
Heating energy [kWh_t]	10143	10150	13328	11148
Electricity for fans [kWh_e]	6478	3757	3728	2951
Primary energy [kWh]	24200	18302	21418	17552
Index of overheating [°C·h]	1053	1164	293	255

In the week on the right, in which the outside air temperature is often higher than 26 °C, the ventilation flow rate is almost always to the maximum permissible value and tends to decrease - although never to the value of the base ventilation - only at night, when the indoor air temperature equals the set point (26 °C). During the central hours of the day the ventilation system keeps the indoor air temperature 1-2 °C above the outdoor air temperature.

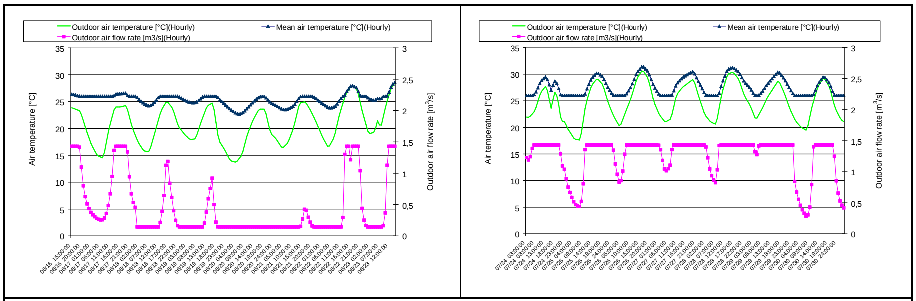

Fig. 4 Hourly profiles of indoor air temperature and outdoor air flow rate for case 2 for one week in june (left) and one week in august (right)

The adoption of the concrete walls of case 3) makes it possible to greatly reduce the index of overheating of the structure, compared with a modest increase in the energy consumption for heating, which in any case can be reduced through the thermal insulation (Table 1).

From the parametric analyses on the insulation thickness of the walls and on the roof (cases 2.1, 2.2, 2.3, 3.1, 3.2, 3.3, 3.4), it can be seen that beyond 5-10 cm there is not any additional benefit, and the effect on the summer behavior is negligible. A greater reduction of the energy needs for heating can be obtained with the increase of the thermal insulation of the roof in case 2), since the roof is the larger heat transfer surface.

Following the previous results, a further configuration was analyzed (case 4) which is characterized by the use of concrete walls, weakly insulated (5 cm), and the roof insulated with 15 cm. This case has (Table 1) a low heating energy consumption (11,148 kWh), a low electricity consumption for ventilation (2,951 kWh) and a summer behavior which limits considerably the overheating (index equal to 255 °C·h).

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Finally, the last evaluation was conducted on the installation of a monocrystalline PV array on the pitch roof. It emerged that, given the large available surface area (over 90 m^2) the amount of the total annual electricity is high (14,788 kWh_e/y) and equal to about 4 times the ventilation consumption (of case 2), however the analysis of the time variable profiles of electricity production and fans electricity requirement, showed that only a modest amount of electricity produced by photovoltaic (1795 kWh_e or 12%) is consumed, and therefore up to 52% of the electricity required for ventilation (1962 kWh_e) has still to be taken from the electricity grid.

4. Conclusions

In the present work, dynamic simulation methodologies, widely adopted in the sector of civil buildings, were applied to a building for animal production characterized by a high degree of standardization. A series of critical issues that merit further investigations are related to the consideration of the latent load due to animals and animal manure, whose values are dependent on the values of indoor temperature and relative humidity, quantities that in turn are unknowns at each time step of the simulation in free running conditions. The results emerged in this study are similar to the ones of other research works, for example [6], and in particular the need to use building materials with sufficient thermal capacity in order to ensure the cooling of the structure through mechanical ventilation with outside air. Optimization of the building structure will then be associated with appropriate measures, where necessary, for the dedicated cooling of sows [7]. The study also revealed that it is necessary to move from a design approach based on few points or, at most, design days, to long-term analysis of the indoor temperature and humidity, in order to take into account the critical behavior of the structure and plants in mid-seasons, when warmer and colder days may alternate.

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