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Energy performance and indoor environmental control of animal houses: a modelling tool

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Abstract

The energy-related products Directive (ErP) 2009/125/EC has set a new generation of equipment that are more energy efficient and reliable. In the case of climate control for livestock housing, a key role can be played by EC motors direct drive variable flow fans that can be used instead of traditional AC fans in applications like broiler or dairy houses. The energy consumptions of such fans strictly depend on the specific application and on the outdoor weather conditions, and there is therefore the need to forecast their energy performance by means of computational tools. In this work, we present a tool developed by the Authors and based on a dynamic model for the estimation of the global (electricity, natural gas, etc.) annual energy consumption of a system installed into an animal house. The calculation is based on a customization of the ISO 13790 Standard simplified hourly model for the energy performance assessment of broiler houses.

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Keywords: Indoor environmental control for animals; Livestock housing; Livestock ventilation; Energy performance of livestock houses.

1. Introduction

The control of the indoor environment of livestock buildings is based on the ventilation, heating and cooling of the houses following time variable temperature, humidity and air velocity requirements that vary as a function of the animal species and ages, the production process, the occupancy ratio, the outdoor conditions. Since the indoor heat load changes considerably, the strategy and the air flow rate of the ventilation are constantly updated in order to guarantee the base ventilation, the relative humidity control and the temperature control. If there is a deep knowledge of the design process that leads to the

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specification of the fan number, the control curve, etc., breeders and investors have less or no information on the annual energy performance of the systems installed in the house.

The energy-related products Directive (ErP) 2009/125/EC has set a new generation of equipment that are more energy efficient and reliable. In the case of climate control for livestock housing, a key role can be played by the new generation of EC (Electronically Commutated) motors that use the technology of permanent-magnet brushless DC motors with direct drive, turning at the same revolution speed as the optimum propeller speed, and that can be used instead of traditional AC fans in applications like broiler, hog and dairy houses. The greater initial cost of such equipment is compensated during the expected lifetime by the substantial energy savings that can be achieved with this technology. However, since the operating conditions of such fans – and the following energy consumptions – strictly depend on the specific application and on the outdoor weather conditions, there is the need to forecast their energy performance by means of computational tools. In this work, we present a tool developed by the Authors and based on a dynamic model for the estimation of the global (electricity, natural gas, etc.) annual energy consumption of a system installed into an animal house. The calculation engine is based on a customization of the ISO 13790 Standard simplified hourly model and can be used for the long term energy performance assessment of broiler houses.

Typically, a batch in a broiler house starts with chick aged some days and terminates after a period of 40-50 days with the selling of the broilers ready for the market. Between one batch and another, an empty period of a week is usually devoted to the cleaning and disinfection of the house. During the year, various batches (7 to 8) can be performed. During a single batch, chicks grow and the internal gains and indoor temperature set point vary consequently. The bird age and internal gains emission also affect the ventilation strategy. Basically, two ventilation modes are used: a *base ventilation* (where the air flow is a function of the bird age) is used when the scope of the ventilation is solely the indoor air quality, while an air flow value greater of the one of the base ventilation is used for cooling purposes. In this last case, since the fans are usually placed at one end of the house, which is very long, this ventilation strategy is called *tunnel ventilation*.

2. Materials and methods

In order to predict the indoor environmental conditions and the performance of the energy systems installed in an animal house, there is the need to build and use detailed models into energy simulation programs (e.g. EnergyPlus [1], TRNSYS) of the envelope construction and of the systems. Frequently, the simplification assumptions underlying in these software tools, even if detailed, prevent the model to appropriately describe the thermal behavior of the system under consideration. This is the reason why self made models are preferred rather than building simulation tools [2].

In this paper, a dynamic model developed into the Excel environment for the estimation of the global (electricity, natural gas, etc.) annual energy consumption of a system installed into a broiler house is presented. It is based on the simplified dynamic model of the normative standard ISO 13790. This model was considered sufficiently detailed with regard to the thermal modeling and able to be customized to a large degree (that may not be straightforward in standard simulation tools) as regards the control of ventilation flow rates and temperature set points.

The model is based on the input specification (thermophysical properties of the house envelope, occupancy and weight gains schedules of the animals, sensible and latent heat production of the animals, ventilation schedules – base ventilation and tunnel ventilation – and control). The calculation is based on the solution, for each time step, of the air heat balance and calculation of the heating/cooling load or the free running temperature, then for each time step, the moisture balance is computed. The results section reports the heating energy requirement, the electricity requirement for ventilation and the global energy consumption and other performance indicators (energy costs, etc.).

The model performs an annual simulation over a complete year under typical weather conditions (e.g. TRY-Test Reference Year data), that is 8760 hours.

2.1. Thermal modeling of the house

The thermal modelling of the house was done by applying the simplified dynamic model given in the international Standard ISO 13790 (Energy performance of buildings—calculation of energy use for space heating and cooling) and that is based on an electric equivalent network made up of five resistances and one capacitor [3]. The testing of this model can be found in Roujol et al. [4] where the BESTEST method and also experimental data were used. Despite the fact that it is less detailed than other, more sophisticated simulation tools (e.g., EnergyPlus), especially as regards the assessment of the total thermal capacity of the building and the effect of the solar radiation, this model was adopted since it performs an hourly calculation of heating and cooling loads and it is implemented into a spreadsheet, which makes it easy to modify and implement other calculations (e.g. for the fans electricity consumption).

The main assumption of the thermal zoning is that all the broiler house is considered as a unique thermal zone of a rectangular shape. The input data (**step a**) are the ones regarding the house and windows dimensions, the U-values of walls and windows and the optical properties of the windows.

2.2. Boundary conditions

The production characteristics inputed are the number of birds and stocking density, the duration of each batch, the empty days between batches. From these input data, all the necessary schedules are created by the tool. First the day bird age is computed, then the yearly schedules (8760 values) of every input variable (**step b**) regarding the occupancy such as bird weight, sensible heat production, vapour production, etc. are computed as a function of the day bird age. All the necessary relations between the day bird age and the various quantities were determined creating appropriate functions from table data by regression analysis. The equation of the bird weight W as a function of the bird age b is

$$W = -0.000021\, b^3 + 0.00256\, b^2 - 0.0053\, b + 0.0708 \text{ [kg]} \quad (1)$$

and was computed reducing the least square errors from data provided from Lohmann Meat [5]. Then, the total heat emission q_{tot}, can be found as a function of the bird weight [5], as

$$q_{tot} = 10\, W^{0.75} \text{ [W]} \quad (2)$$

The upper and lower limits of indoor air set point temperatures and the upper and lower limits of indoor air relative humidity are complex functions of bird age and are reported in Figs. 1 and 2. Once that the temperature is defined, for each time step, it is possible to split the total heat emission into the sensible one and the latent one by computing, in compliance with [6], the ratio between sensible and total heat (**step c**) which varies between 0.43 and 0.56.

2.3. Modelling of the ventilation and of the temperature control

There are two different types of ventilation that are implemented into the tool, the base ventilation and the tunnel ventilation for cooling purposes. The base ventilation (**step d**) flow rate specific to the bird weight is computed as a function of the bird age with the following equation

$$V_w = 0.00000036\, b^4 - 0.000066\, b^2 + 0.0046\, b^2 - 0.152\, b + 2.467 \text{ [m}^3\text{h}^{-1}\text{kg}^{-1}\text{]} \quad (3)$$

which was determined by regression analysis on values from Cobb [7]. Then, the base ventilation flow rate is

$$V = V_w \, W \quad [m^3h^{-1}] \tag{4}$$

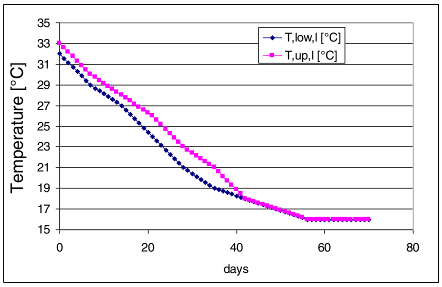

Fig. 1. Air temperature set point range

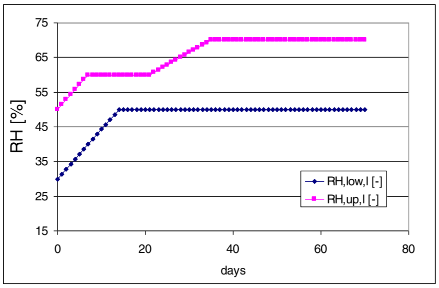

Fig. 2. Relative humidity set point range

V is the value that, apart the periods of void for sanitary reasons, is always maintained in the house. At next stage (**step e**), the model solves the air heat balance for the determination of the ambient load (heating/cooling load) considering as set point temperatures the limits of Fig. 1. In particular, the lower set point is assumed as the heating set point and the upper set point is assumed as the cooling set point with a dead band between them. At this stage the heating/cooling load is theoretical and for each of the 8760 hours of the simulation, one of the possible three conditions happens:

1) the air temperature is equal to the lower set point temperature and there is a heating load;
2) the air temperature falls within the dead band between the lower and the upper set point temperatures and there is no heating/cooling load (free running conditions);
3) the air temperature is equal to the upper set point temperature and there is a cooling load.

Conditions 1) and 2) represent realistic cases while condition 3) is theoretical because there is not a mechanical cooling system installed in the house, so this result will be used for later calculations.

When condition 1) happens, the model stores the value of the hourly heating load q_h in order to compute the heating energy needs Q_h; the electricity for ventilation is computed with reference to the base ventilation. In case of condition 2), the model considers that there is only an electricity need for ventilation, that again is computed considering the base ventilation. When condition 3) happens, the model considers the cooling load q_c a cooling load that may be satisfied by free cooling with the outdoor air and computes the outdoor air flow rate V_{tv} that may be necessary to reduce the indoor temperature T_i up to the upper set point temperature $T_{,up,l}$ as

$$V_{tv} = \frac{q_c}{1.01\,(T_i - T_{a,out})}\frac{1}{\rho} \quad [m^3h^{-1}] \;\; \text{if } T_i - T_{a,out} > \Delta T \tag{5}$$

provided that the outdoor air temperature $T_{a,out}$ is sufficiently lower than the indoor air temperature. The temperature differential ΔT between the indoor air temperature and the outdoor air temperature (e.g. 0.5 °C – 3 °C) can be set by the user. The outdoor air ventilation flow rate considered in the air heat balance (**step f**) is increased and the indoor temperature conditions are updated and fall between the set point limits. When the constraint of Eq. (5) is not satisfied, that is, there is a cooling load but the outdoor air temperature is greater than the indoor temperature, the evaporative cooling system is activated. In the model, this is simulated assuming that the ventilation flow rate is set to the maximum value.

2.4. Modelling of the fans

In order to perform the calculations of heating and electricity energy needs, it is necessary to know the performance parameters of the systems installed. As regards the heating (**step g**), an air heater equipped with a fuel burner and with a 100% conversion efficiency is considered. As regards the ventilation (**step h**), the specifications of some commercial products of Munters, tested by the University of Illinois Department of Agricultural and Biological Engineering, where the air flow and the specific electricity consumption are reported as a function of the static pressure (from 0 to 60 or 75 Pa) were adopted. For the base ventilation, the products ED24HE, ED30HE and ED36HE were selected, while for the tunnel ventilation the products EM50 1 hp and EM50 1.5 hp were selected. The latter fans are in compliance with the energy-related products Directive (ErP) 2009/125/EC. The static pressure of the base ventilation is entered by the user, while the static pressure of the tunnel ventilation is computed as a function of the air velocity as

$$p_d = (0{,}0257\, v^2 + 0{,}0031\, v + 0{,}006)\cdot L \quad [\text{Pa}] \tag{6}$$

where v is the air velocity and L is the length of the house. In case of evaporative cooling, a further pressure drop for the evaporative cooling pads is summed to the value of Eq. (6). The user enters the design static pressure of the tunnel ventilation in order to size the total number of fans. The hourly electricity consumption of the tunnel ventilation fans is given by Eq. (7) where the specific fan performance SFP is hourly variable as a function of the static pressure.

$$E_{f,tv} = (V_{tv} \,/\, SFP)\ 1000 \quad [\text{kWh}] \tag{7}$$

2.5. Final results

The hourly values of heating load and power consumption for ventilation are integrated during the year in order to have the heating energy need and the electricity need for ventilation (**step i**). Once assigned the specific cost of each fuel and of the electricity, some financial indicators can be computed.

3. Application to a case study

The application of the model to a case study is presented. It is a broiler house of 1680 m^2 located in the province of the Torino location in the North-West of Italy. The two lengths of the house are 120 m and 14 m, the side wall height 2.5 m. The mean U-value of the walls is 0.68 W/m^2K, the one of windows 3 W/m^2K. The stocking density is 17.9 birds/m^2 and the batch duration 42 days. Weather conditions refer to the TMY IGDG for the Torino location. The heating load resulting from the calculations is plotted in Fig. 3. The total energy need for heating is equal to 133 kWh/m^2a and it is mainly due to the heating of the outdoor air for the base ventilation (that explains the heating load in summer). In Fig. 4 the base ventilation flow rate is reported against the tunnel ventilation flow rate. It can be noted that the base ventilation flow rate varies as a function of the bird age and occupation, and reaches the maximum value of 39,000 m^3/h at the end of each bathc while the tunnel ventilation flow rate is climate dependant and tends to be at the maximum value, which is equal to 285,000 m^3/h (more than 7 times greater). The base ventilation electricity consumption varies from 3.6 to 7.5 kWh/m^2a as a function of the each different alternative (5 ED24HE fans or 3 ED30HE or 3 ED36HE). The electricity use for ventilation is lower in case of new fans that are in compliance with the ErP Directive (ED24HE and ED36HE) than in the case of standard fans (ED24 and EM36). In particular, using the ED36HE instead of the EM36 brings to a saving of 93 €/y (31 €/y*fan) with a constant electricity cost of 0.18 €/kWh. As regards the tunnel ventilation, also in this case different alternatives are available (9 EM50 1 hp, 8 EM50 1.5 hp, 8 EC52 1 hp, 7 EC52 2 hp). In particular, some fans are new high efficiency fans in compliance with the ERP-Directive (EM 50 and EM 52). The yearly performance was determined integrating the hourly results of Eq. (7), giving results from 8.4 to 11.2 kWh/m^{2}a, and the electricity cost was determined assuming a specific cost for electricity equal to 0.18 €/kWh$_e$. The more efficient product (EC52 1 hp) reduces the energy consumption of about 40% which results in an annual financial saving of 1660 €/y.

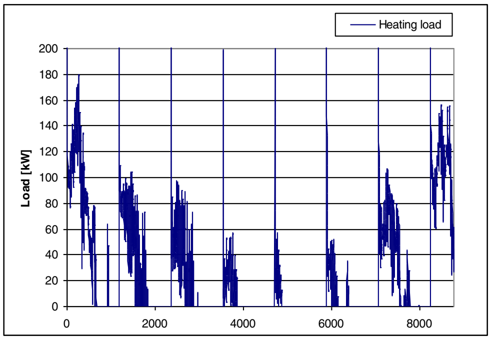

Fig. 3. Heat load profile

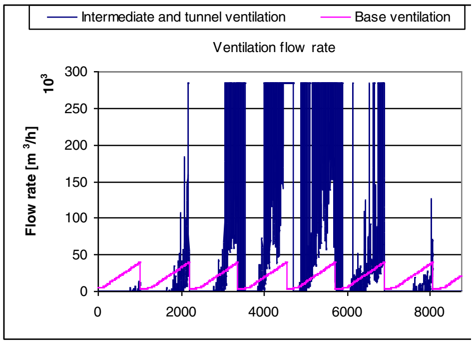

Fig. 4. Base ventilation and tunnel ventilation flow rates

4. Conclusions

The basic features of a tool for the determination of the long term energy performance of a fan system installed into an animal housing units were presented. The authors are now working in order to compare and contrast the model with experimental data under controlled conditions in order to validate the tool. Also indexes of animal stress and wellbeing may be easily implemented in the tool.

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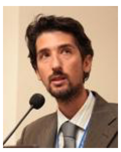

Biography

Enrico Fabrizio (Torino, 1978), PhD in Energy Technology at the Politecnico di Torino and at the INSA de Lyon, is assistant professor at the Department of Agricultural, Forest and Food Sciences of the University of Torino since 2008.