Modelling the energetic performance of a pig stable

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Abstract:
Agriculture and intensive farming are a large source of green house gas emissions. Since currently about 70% of its energy is coming from polluting fossil fuels, it is necessary to implement renewable technologies in stables, which is currently being investigated with the RES4LIVE project. Some of the possibilities are: photovoltaic and thermal solar panels, heat pumps, ventilation energy recovery, wind energy and manure energy recovery. To evaluate the extent to which these technologies can be used and combined, and to estimate the performance and cost, a thermal model is being developed. This numerical model (although not CFD) is currently focused on pig stables and takes different heat losses (through ventilation and through the building envelope) and heat gains (heating systems and heat generation by the animals) into account. The results are still preliminary, but the goal is to accurately determine the heating and cooling load of each zone in the stable. This will eventually allow to make a selection and sizing of the proper renewable technologies.

Keywords:
Agriculture; Intensive farming; Renewable technologies; Modelling; Energy recovery.

1. Introduction

One fifth of the global pork production takes place in Europe [1]. Around 24 million tons of pig meat were produced in Europe in 2019 [2]. To ensure healthy pigs and maximize the growth rate, ventilation of the barn should guarantee an optimal indoor air quality, while also the barn temperature should be in the thermal neutral zone of the pigs. In Fig. 1, it is illustrated how excessively low or high temperatures can lead to hypothermia or hyperthermia of the animals [3].

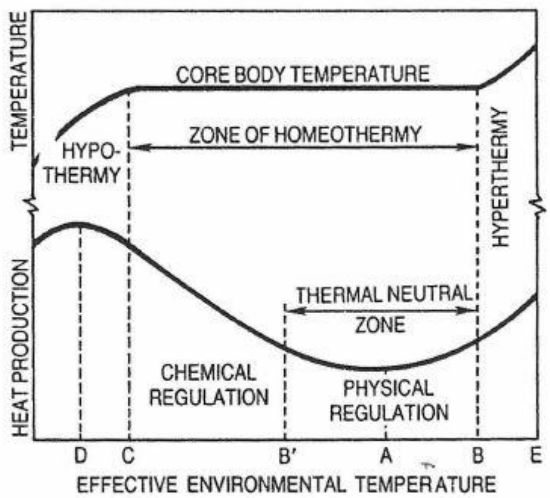

Fig. 1. Illustration of the influence of the environmental temperature on the body temperature and heat production of pigs. [3]

To ensure the comfort of the pigs, the European agricultural sector still heavily relies on fossil energy inputs [1]. In 2018, 84% of the final energy use in farming came from a fossil energy source. The combustion of the fuel inevitably leads to the production of green house gas emissions, contributing to global warming.

In order to reduce the fossil fuel use, the heating and cooling loads of the barns should be reduced and renewable energy sources can be implemented. To reduce the loads, more insulation can be installed and the air tightness can be improved. Furthermore, ventilation losses (or gains) can be reduced by the installation of a heat exchanger, preconditioning the supply air with the exhaust air. Some possible renewable energy sources are wind and solar energy. Especially solar energy is promising, since barns typically have large roof areas, and solar panels can provide electricity (PV panels), thermal energy (solar collectors) or both (PVT systems). To further reduce the fossil fuel consumption, the gas (or oil) boiler can be replaced with a heat pump. Different configurations are possible, where the heat is e.g. supplied by outside air or by the thermal energy in the soil. Heat pumps also have the advantage of being able to cool and heat at the same time.

The challenge of installing these sustainable technologies is however in the proper sizing. Gas boilers are typically slightly overdesigned, to ensure the comfort conditions. Overdesigning of the heat pumps will however lead to a reduced efficiency and a significantly higher cost. Additionally, while some zones in the stable might require heating (e.g. piglets), others might require cooling (e.g. sow). Therefore, a detailed model of the stable is a convenient tool in determining the loads.

Different models can be found in the available scientific literature determining the indoor climate and energy use of barns, covering both computational fluid dynamics (CFD) studies [4-5] and steady state balance models [6-8]. These are however often developed for poultry barns, and usually consider a single-room homogeneous barn. Therefore, a new stable model is developed, focussed on pig barns, where the different compartments of the stable are considered as separate zones. For all zones, the energy balance will be calculated, assuming quasi steady-state conditions. The temperatures and humidities are determined, while some local parameters e.g. local air velocities are not considered (in contrast to CFD studies).

2. Stable model

In this study, a detailed model is developed to assess the heating and cooling load of a pig stable, containing different types of pigs. This model, programmed in Python, is based on a real stable, operated by ILVO (Flanders Research Institute for Agriculture, Fisheries and Food) , but also serves commercial purposes. It is located in Merelbeke, Belgium, measures 2380 m² and has a total capacity of 105 sows, 600 piglets and 750 fattening pigs.

The model developed in this study is a quasi steady-state model (no CFD was performed), taking into account the heat generation of the animals $\dot{Q}_{animal}$, the conduction $\dot{Q}_{cond}$ and infiltratrion losses $\dot{Q}_{inf}$ through the building envelope to the environment, the ventilation losses $\dot{Q}_{vent}$ and the heat supplied to the piglets by floor heating $\dot{Q}_{floor}$ and heating lamps $\dot{Q}_{lamps}$. These heat transfer rates are determined at the set-point temperature of the zone, dictated by the age and type of the pigs in the zone. To accommodate the additional heat load, tubes are installed in the supply air channels to preheat the incoming air. Through these tubes, water at 70°C is flowing. The heating or cooling load $\dot{Q}_{load}$, that should be supplied by e.g. the tubes in the supply air or by different means, is calculated with Eq. (1). When $\dot{Q}_{load}$ is positive, cooling is required, and when $\dot{Q}_{load}$ is negative, heating is required.

$$\dot{Q}_{load} = \dot{Q}_{animal} - \dot{Q}_{cond} - \dot{\mathrm{Q}}_{\mathrm{inf}} - \dot{Q}_{vent} + \dot{Q}_{floor} + \dot{Q}_{lamps} \tag{1}$$

It should be noted that in the real barn of ILVO, no cooling system is present. Even more, some zones also do not provide any heating. For these areas, $\dot{Q}_{load}$ should thus be zero. This is achieved by changing the zone temperature (away from the set temperature) until the heat generated by the animals (and possibly floor heating or heating lamps) matches the envelope and ventilation losses.

2.1. Animal related calculations

A first factor that is taken into account is the heat produced by the animals. Their total generation rate $\dot{Q}_{animal,total}$ is depending on the type of pig, their age or weight and the temperature in their zone. For the determination of the total heat production of the animals the reader is referred to the dedicated literature [9-10].
This total heat generation rate is then divided in a sensible $\dot{Q}_{animal}$ and latent $\dot{Q}_{animal,latent}$ part according to Eqs. (2) and (3):

$$\dot{Q}_{animal} = \dot{Q}_{animal,total} \cdot [0.8 - 1.85 \cdot 10^{-7} \cdot (T_{zone} + 10)^4)] \tag{2}$$

$$\dot{Q}_{animal,latent} = \dot{Q}_{animal,total} - \dot{Q}_{animal} \tag{3}$$

Additionally, also the zone set temperature (T_{set}, °C) and the minimal and maximal ventilation rates (V_{min} and V_{max}, m³/s) are dictated by the animals [9-10].

2.2. Building envelope losses

Heat losses (or gains) occur through the walls, the roof and the floor, to the environment ($\dot{Q}_{cond} = \dot{Q}_{wall} + \dot{Q}_{roof} + \dot{Q}_{floor}$). The heat losses through the wall and roof are a combination of a convection and conduction problem and are calculated with Eqs. (4) and (5). The conduction (and convection) losses through the wall are calculated in the same fashion, but taking a correction factor b (typically 0.8) into account (Eq. (6))

$$\dot{Q}_{wall} = \frac{A_{wall}}{R_{conv,ext} + R_{wall} + R_{conv,wall}} \cdot (T_{ext} - T_{zone}) \tag{4}$$

$$\dot{Q}_{roof} = \frac{A_{roof}}{R_{conv,ext}+R_{wall}+R_{conv,roof}} \cdot (T_{ext} - T_{zone}) \tag{5}$$

$$\dot{Q}_{floor} = \mathrm{b} \cdot \frac{A_{floor}}{R_{floor}+2 \cdot R_{conv,floor}} \cdot (T_{ext} - T_{zone}) \tag{6}$$

Additionally, there are also infiltration losses through the building envelope to the environment. To determine these, we use a fixed number of air changes per hour (ACH). A value of 1 was used for our reference barn, since it is a recently constructed and well insulated building. The losses for a zone with volume V (m^3) is calculated with Eq. 7. The properties of the air, like density ρ and enthalpy h, are calculated with the property database package CoolProp [11].

$$\dot{Q}_{inf} = \frac{\mathrm{V} \cdot \rho \cdot \mathrm{ACH}}{3600} \cdot (h_{ext} - h_{zone}) \tag{7}$$

2.3. Ventilation losses

The ventilation losses $\dot{Q}_{vent}$ are calculated with Eq. (8), where $\dot{m}_{vent}$ is the mass flow rate of the ventilation air in the considered zone (kg/s), while h_{supply} and h_{zone} air the enthalpy of the supply air and the air inside the zone.

$$\dot{Q}_{vent} = \dot{m}_{vent} \cdot (h_{supply} - h_{zone}) \tag{8}$$

It can be seen that when the temperature (or enthalpy) of the air inside is higher than the temperature (or enthalpy) outside, that the ventilation losses will be negative. In the other case, there will be heat gains by the ventilation.

The minimum and maximum volume flow rates are determined by multiplying the number of animals with their respective ventilation rates, as explained in section 2.1. During winter, the ventilation rates are kept as low as possible. As soon as heating would be required, ventilation rates are increased to minimize $\dot{Q}_{load}$. From certain outside temperatures on, the ventilation rate will be maximal and $\dot{Q}_{load}$ will start to increase.

In the current version of the model, there is no heat recuperation on the ventilation air, so the conditions of the air supplied to the zone or heating system are equal to the outside air conditions.

2.4. Additional heat sources

In the zones with piglets, floor heating is present. Since limited information is available on e.g. the flow rates of water through these systems, the floor heating is currently modelled with a fixed heat output. In the weaned piglet area, a power of 2880 is considered, while for the older piglets, a power of 1800 is used. This assumption makes sense given that the temperature in these zones is fairly constant throughout the year, as well as the water flow rate and inlet temperature.

Additionally, when the piglets are less than one week old, heating lamps are turned on in order to guarantee thermal comfort of the animals. These lamps are modelled with a fixed power output (per compartment) of 2800 W for the first two days and 1400 W for the next 5 days.

3. Case study

As explained before, the presented model is based on an existing stable in Belgium. In this stable, with 24 zones in total, there are 16 zones for fattening pigs, 2 zones for weaned piglets, 3 zones for growing piglets, 2 zones for sows and a quarantine zone. The zones with only sows and the quarantine zone do not have any heating system installed. In reality, no cooling system is installed.

To accurately simulate the outside conditions, a "typically meteorological year" (TMY) weather file is retrieved from a tool provided by the EU Science Hub [11], supplying the outside air temperature and relative humidity for one year with time steps of one hour. For the quasi steady-state calculations, the same time steps of one hour were used.

The results presented below are generated by the model with settings matching reality as close as possible (e.g. no heating in the zones with only sows). Real data about the number of animals (and their age) in each zone are used.

3.2. Total heat loads

According to the performed simulation for one entire year, the total heating (including floor heating and lamps) and cooling load of the barn are 157 MWh and 85 MWh. The peak heating and cooling power are 112 kW and 139 kW respectively.

The division of the heat load over the air preheating, floor heating and heating lamps is shown in Fig. 2.

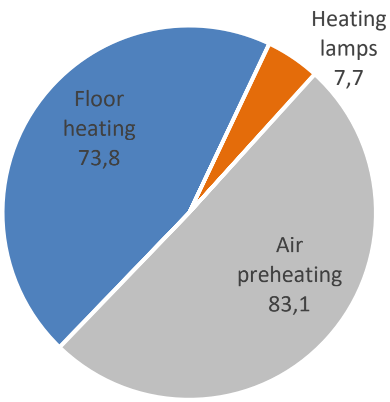

Fig. 2. Division of the total heat load for one year over the air preheating, floor heating and heating lamps (values in MWh).

In Fig. 3, the heating loads per month and their division of the type of zone is given.

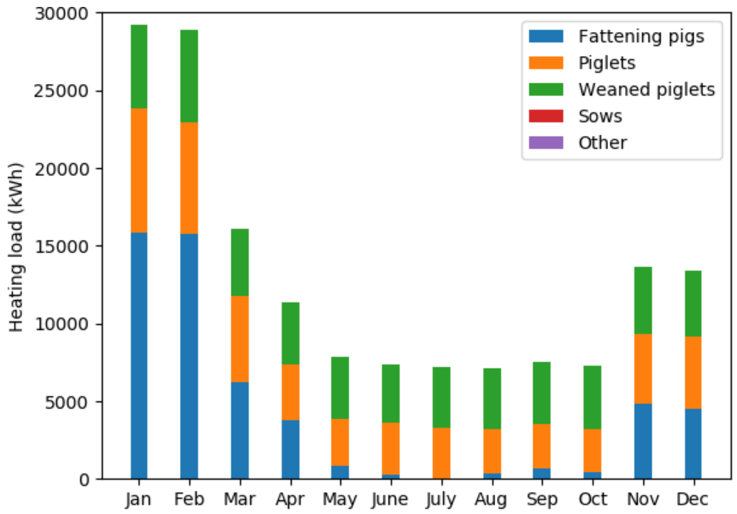

Fig. 3. Heating loads per month per zone type

3.3. Validation

Currently, only limited measurement data is available to validate the obtained results. Only the gas usage per month of the stable (for 4 years) is known. The calculated heating loads per month are compared with the energy use of the gas boiler in Fig. 4. This energy use is calculated from the gas consumption, taking a correction for the efficiency of the boiler (94%) into account and subtracting the estimated heat use of the domestic hot water (mostly showers) of the stables. It can be seen from this figure that, although some differences, the model is able to predict correct order of magnitude of the heat load and that this heat load seems to follow the right trend.

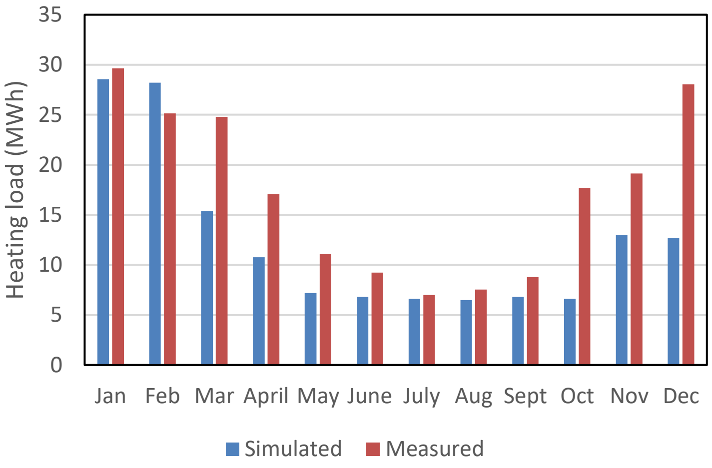

Fig. 4. Comparison of the calculated heat load with the average heat load determined with the gas meter data of 4 years.

There appears however to be an underestimation of the heat load, which can have several causes: an overestimation of the heat generated by the animals, an underestimation of the environmental and ventilation losses (the real ventilation rates are not known), some distribution losses of the heat and differences between outside temperatures. The fine-tuning of the model is currently work in progress.

A validation of the cooling load is currently not possible as no cooling system is installed in the real barn.

4. Conclusion

In this paper, a quasi steady-state balance model is presented to estimate the heating and cooling loads of a pig stable. The model takes the heat produced by the animals, as well as conduction, infiltration and ventilation losses into account. The preliminary results indicate that the obtained values match the real heating load to a certain extent. The model is currently however still under development and some finetuning of different parts is required.

The goal of the model will eventually be to assess the feasibility of renewable energy sources and energy-efficiency measures. The first technologies that will be evaluated are: air-to-air heat recovery, solar panels, thermal storage and the implementation of a heat pump.

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