Application of urban passive cooling systems and design techniques in livestock buildings

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Abstract. A protected environment for plant and animal growth is necessary for the increase of agricultural production. The expanding number of agricultural structures with a controlled environment, such as greenhouses and livestock structures, might be the key to tackling the continuously increasing food demand due to the growing population. Farm animals bred inside environmentally controlled buildings are positively affected. It has been found that farm animals have shown dramatic reduction in their productivity resulting in economic losses when the temperature rises beyond the upper critical point of their thermoneutral zone. For this reason, cooling systems and design techniques are developed and used in livestock buildings, in order to keep the optimum growth environmental conditions (temperature and humidity), so as to avoid heat stress. Conventional energy, which is the main energy source consumed by the active cooling systems might not be economically viable and additionally it has negative effects on the environment. Therefore, passive cooling methods towards the sustainability of livestock building designs are being examined, since the viable development of the economic factor is crucial. The most usual passive cooling systems are based on shelters, insulation, natural ventilation as well as architectural parameters, affecting the cooling of a building, such as the roof inclination, the wall colour, the orientation etc. Hybrid systems, such as earth to air heat exchangers are also used. There are some passive cooling solutions that have been used with success in urban buildings and these may be quite effective for livestock buildings without excessive modifications. The present study focuses on a description and evaluation of these solutions in primary food production.

1. Introduction

The global population that quadrupled during the last century is likely to reach 9.7 billion by 2050. This growth is driving up global food demand, which is expected to increase from 59% to 98%, within the same period [1]. Farmers worldwide will need to increase crop and animal production adopting new methods like precision farming, or what is called ‘sustainable intensification’. These methods must take into consideration urbanization, advanced logistics, transportation, storage, climate change while focusing on reduction of the negative environmental impacts which are stretching resources. For example, heat stress is a common phenomenon for livestock during weather with extremely high temperatures. Heat stress can affect the animals’ welfare and health, may reduce livestock feed intake and growth, resulting in lower production and difficulties with reproduction. St-Pierre et al. [2] found that the annual livestock and poultry industry losses, due to heat stress, ranged between $1.69 and $ 2.6
billion. For these reasons it is considered to be very important to investigate management practices which could mitigate heat stress effects on livestock.

The basic elements of the thermal environment that affect animal welfare and production are temperature, air movement, humidity and solar radiation. Farm ‘homeothermic’ animals should be bred in conditions within their thermoneutral zone, in order to manage maximum and high productivity. A thermoneutral zone can be defined as the temperature zone within which animal growth and production is independent of the ambient temperature. This zone is bounded by a lower critical temperature and an upper critical temperature. The lower critical temperature is the air temperature which must be maintained at all times to ensure that feed energy is not diverted unnecessarily for production purposes. The upper critical temperature is the air temperature which must not rise higher as in this case animals are unable to profitably exploit their feed.

The chemical environment is also a parameter which affects animal production. In a livestock building the poison gases from manure and urine etc. negatively affect the production and it is obvious that to control the environment inside a livestock building is more complicated than a residential building since more parameters are involved.

Both building categories, urban and livestock need cooling systems and design techniques to decrease the inside temperature during hot periods. The replacement of artificial cooling systems by some of the passive cooling ones is a crucial factor since it decreases the cooling load by up to 50% - 70% in residential buildings [3] and significantly reduces CO₂ emissions [3][4]. Another point is that passive cooling systems are suitable for the sustainability of livestock buildings positively affecting the viable development of animal production, which is considered to be a significant economic factor. In passive cooling systems the energy flow is realized naturally, for example by conduction, convection or radiation or a combination of them, without using electric device.

This work describes some of the urban passive systems that are applicable in livestock buildings.

2. Passive cooling systems in livestock buildings
The passive cooling technologies used in livestock buildings face more difficulties and restrictions than those in residential buildings. The main reasons are the following:

- They need to maintain the interior thermal environment within the range of animals thermoneutral zone.
- They need to remove toxic chemicals keeping the composition of the indoor air at normal levels.
- Their cost should be kept low.
- Insulation materials for livestock buildings should be resistant to rodents, pests and birds.
- Animals are not able to manage the control of their environment like humans. Therefore the systems used must be effective themselves throughout 24 hour period.

All the above affect production costs, which must be kept as low as possible to enable the animal products to be competitive. In fact, some of the passive cooling systems and the design techniques that are already used in livestock buildings have many similarities with those in residential ones.

3. Energy balance in livestock buildings
The first law of thermodynamics is used to express the thermal energy balance of the animal [5]:

\[ MHP \pm J \pm q_{rt} \pm q_{cv} \pm q_{cd} - EHL = W C_p \Delta T_b / \Delta t \]  

(1)

where:

- \( MHP \) = rate at which thermal energy is produced by metabolism
- \( J \) = rate of mechanical work
- \( q_{rt} \) = rate of heat transfer by radiation
- \( q_{cv} \) = rate of heat transfer by convection
- \( q_{cd} \) = rate of heat transfer by conduction
\[ EHL = \text{rate of heat loss by evaporation of water} \]
\[ W = \text{body weight} \]
\[ C_p = \text{specific heat of the body mass} \]
\[ T_b = \text{body temperature} \]
\[ t = \text{time} \]

Equation (1) is a fundamental expression which links the physiological state of the animal and the thermal environment (figure 1). To control the temperature, humidity and ventilation of a livestock building this must be considered as enclosed space, where the energy balance is given by the following equation (2):

\[ q_a + q_{sh} = q_b + q_v \tag{2} \]

where:
\[ q_a = \text{sensible heat produced by animals} \]
\[ q_{sh} = \text{supplementary heat to maintain the inside air temperature} \]
\[ q_b = \text{heat loss through the building’s walls, floor, ceiling, doors, windows, etc.} \]
\[ q_v = \text{heat loss by ventilation} \]

So, the heat losses are structural heat losses and ventilation heat losses:

Total heat loss = structural heat loss + ventilation heat loss

According to equation (2) structure and ventilation are the main parameters, which should be considered in a passive cooling system or design technique.

**Figure 1.** Heat exchange between animals and their environment.

**Figure 2.** Roof insulation and natural ventilation in a greenhouse type livestock building.
4. Passive cooling systems and design techniques already used in livestock buildings

4.1. Insulation
When trying to cool a building it is necessary to prevent the flow of heat from the outdoor to the indoor environment. Livestock insulation is one of the most essential techniques to support and maintain high standards of living environment for farm animals. As well as managing the heat flow between the indoor and outdoor environment it also, manages moisture, fungus, cold and condensation in the same way. The absence of insulation results in decreasing air flow, humidity increase, sudden temperature rise or fall and decline in performance. Therefore effective insulation is the most efficient method to reduce energy consumption.

In Mediterranean, subtropical and tropical climates, where the warm seasons are intense and extended, the cooling needs for livestock buildings are increased. The insulation of a constructive element is related to its thermal resistance and by increasing the thickness of the insulation material or reducing its thermal conductivity, the insulation is upgraded.

Insulation techniques applied to livestock buildings do not differ from those used in urban buildings. Roof insulation or whole livestock building insulation play a major role in the internal conditions throughout the whole year so insulation positively affects the production, resulting in lower energy costs, increased animal productivity and comfortable working conditions for humans. The most common insulation materials are polyurethane, expanded polystyrene, mineral wool, cork and cellulose.

Menconi and Grohmann [6] conducted research on an Italian sheep farm studying the performance of various insulating roof materials. The results suggest that the best materials with respect to their entire life cycle are glass wool, sheep wool and hemp fiber, whereas the polyurethane, which is considered one of the best insulating materials, falls into the last place because of its high primary energy input.

The roof is the most important place to start insulating and wall insulation is less important than roof insulation. However floor insulation has little or no effect on cooling. In figure 2 roof insulation is presented.

4.2. Solar shading – Shelters
Reducing the amount of direct sunlight decreases heat-stress behaviour in animals. In the summertime, animals which are not bred in close buildings, seek shelters to avoid the sun.

In rural buildings solar shading techniques are used widely. Similarly sheds for animals compose the simplest passive cooling system. The sheds could be permanent or removable according to the animals’ needs. The height and the total surface depend on the number and species of the animals and the outer
surface of roof should be constructed with materials which reflect solar radiation. This under roof insulation positively affects the animals. The floor is constructed from cement to facilitate manure removal. The width of a shelter must not measure more than 12 m in order to achieve effective cooling of the animals’ environment using natural ventilation. A typical shelter is shown in figure 3.

4.3. Orientation
The proper orientation of a livestock building depends on the local climatic conditions and the prevailing winds. Building orientation seriously affects cooling due to the direction of the prevailing winds. A North-South orientation reduces direct entry of solar radiation into the building, which ultimately helps to keep it cool. If this orientation allows strong winds to enter the building and negatively affect the animals, two solutions are available. Firstly, either changing the orientation to East-West or secondly keeping that of North-South using windbreaks. These should be made of plastic net materials or evergreen trees. The minimum distance between the building and the windbreaks, to avoid shading, is given by the following relation (figure 4):

\[ l = H \cdot \cot \beta \]  

(3)

where
- \( l \): shadow length
- \( H \): height of obstruction (windbreak)
- \( \beta \): solar altitude

Evergreen trees on the South and West sides afford the best protection from summer sun and cold winter winds.

4.4. Shape of the building and roof inclination and colour.
‘Square shaped’ buildings lead to higher levels of heat absorbed by the structure [8]. In addition, roof material temperatures vary according to different roof slopes. A higher inclination of the roof present higher temperatures compared to a lower inclination due to the elevation of the sun [9]. Another factor influencing the cooling of a livestock building is the colour of the roof. The replacement of dark coloured roofs with brighter coloured roofs, significantly reduces the heat stress of the animals [10].

4.5. Natural ventilation
Ventilation is a necessary part of the environmental control system for all animals that are confined in closed livestock buildings. The purpose of ventilation is twofold first, to keep the interior air in the same composition as that of the atmosphere and second, to control the air temperature and humidity. It is clear that ventilation system design requires the integration of the physical and biological sciences. Also, the two engineering design parameters, which must be considered, using fundamental laws and relationships, are (a) the ventilation rates and (b) the airflow distribution.
Natural and forced ventilation are used in livestock buildings, forced ventilation requires a mechanical energy input to produce the pressure differential necessary to cause air flow. However, the use of conventional energy might not be economically viable and often has negative effects on the environment. Natural ventilation is the movement of air through the air openings of a building using the natural forces due to temperature differences or to wind force. Low initial cost and low energy cost of natural ventilation are the main factors that make it the most used type of ventilation. Natural ventilation is not suitable for animals that have a narrow thermoneutral zone or are sensitive to draughts. In these cases, mechanical ventilation to assist a natural one is an acceptable approach.

In livestock buildings the air opening area of natural ventilation should be at least 25% of the floor area. Natural ventilation systems use large sidewall openings covered by curtain or net to control air flow, air velocity and to keep out birds. Chimneys or openings along the ridge are also incorporated to control the air flow rates (figure 2). Adjustable baffles are used above the roof openings to protect the animals from the rain. Natural ventilation systems used in urban buildings have many similarities with those used in livestock buildings.

5. Urban passive cooling systems and design techniques applicable in livestock buildings.

5.1. Earth integrated buildings
The ground temperature is much lower than the air. Therefore, the method of earth integrated buildings means that the inside temperature remains almost constant with little change during the whole year. In warm geographical areas the ground temperature is significantly lower than the air temperature and this difference is enough to keep the building cool thus avoiding the animal heat stress. Earth integrated buildings, suitable for livestock are useful in hot areas provided that dynamic ventilation and light design with windows and skylights exist. The energy input for dynamic ventilation may be much lower than other techniques used to cool livestock buildings in hot climates.

5.2. Wind catcher solutions
Livestock buildings covered with panels like greenhouse type structures, may use wind catchers which are a relatively easy way to cool the inside environment. Two types of catchers are proposed, the panels are cut in the shape of a wind catcher’s base, which is connected to the roof either by bolts and a tensioning part (figure 5) or by perimetrical soldering at the base of the chimney.

5.3. Passive cooling roof in hot arid areas.
An experimental study of passive cooling roofs on urban buildings was carried out in Algeria [11].

The roof was composed of the following materials:

- a metal plate ceiling,
- a bed of rocks which lies over the ceiling in a water pool,
- an air gap over this bed separated from the external environment by an aluminium plate,
- the upper surface of the aluminium plate is painted with a white titanium-based pigment to increase the solar radiation reflection.

The results of this investigation showed that the air temperature can fall from 6 °C to 10°C. This application is suitable for livestock buildings not only with horizontal roofs, but also with arch or span roofs. Figure 6 shows the passive cooling roof in Algeria in a modified version for livestock buildings.
5.4. Earth to air heat exchanger (EAHE) and solar chimney (SC)

The earth to air heat exchanger is used to improve natural ventilation and through a cooling effect decreases the temperature in a building. This system consists of a pipe buried in the ground through which air is sucked into the building. The ground temperature at a certain depth remains almost constant throughout the year therefore, during summer and in the daytime, mainly in hot and arid areas, the soil temperature is lower than the outdoor air temperature.

The proposed system is composed of two parts, the earth to air heat exchanger and a solar chimney. The solar chimney is oriented to the South and is made up of a glass surface and an absorber wall. The EAHE consists of horizontal pipes buried at a specific depth. The solar energy heats up the air in the SC causing the air to flow upwards due to the stacking effect and in this way, it sucks the outside air in through the cooling pipe.

Many research works have been conducted with the use of earth to air heat exchangers (EAHE) for producing cooling air, in fact various analytical models have contributed to the study of the cooling effect of EAHE [12]. Some characteristics of EAHE, such as the length and diameter of the pipe, the depth where the pipes are buried, the pipe materials etc, were also studied [13].

In some cases, earth to heat exchangers are assisted by solar chimneys to implement natural ventilation and passive cooling in buildings. In figure 7 a schematic diagram of earth to air heat exchanger and solar chimney applicable to livestock buildings is presented. These systems sometimes require an amount of energy to force the air flow inside the pipes, so they could be considered as hybrid systems. The amount of energy required is low and can be produced by PV panels or other renewable energy systems, in some cases there is no mechanical assistance referred to in the literature [14].

5.5. Earth to air heat exchangers and wind tower

Many earth to air heat exchangers are assisted by a wind tower for the passive cooling of buildings, mainly in arid and hot climates. The wind tower is a massive structure made of materials of high specific heat. It has two openings, one inlet placed in windward direction and an exit facing the leeward direction. A difference of pressure occurs between the two openings, so the outside air passes through the interior of the building through the inlet opening and continues circulating through the buried pipes of the EAHE, keeping the indoor environment cool.

Many researchers have developed different types of wind towers to assist passive cooling systems in urban buildings. Some of them [15] studied special architectural characteristics for wind towers to be used in Middle East. Others [16] tried analytical approaches and theoretical models or they investigated the performance of wind towers.

In this paper an earth to air heat exchanger, assisted by a wind tower [17] is proposed to be used in livestock buildings (figure 8).
5.6. Vegetation and landscaping
Sustainable building performance in hot climates includes plantation and landscaping as good strategies to block the heat. These strategies are used in urban buildings to reduce indoor temperature where exterior shading can be provided by well-placed trees. The courtyard is a common architectural feature which can modify the microclimate thus improving the thermal comfort conditions of the attached built environment. The shading from trees and vegetation protects the building from direct solar radiation, during the day. In addition, pools and canals nearby the buildings contribute to an evaporative cooling effect. Haggag and Elmasry [18] conducted an analytical study in one of the largest resorts in Dubai in the City of Jumeirah and found that plantation can reduce the air temperature by up to 5°C of nearby buildings. This application is recommended as a very good strategy for livestock buildings since they are located in large agricultural areas that facilitate the above described techniques.

Another promising technique is the ‘Green wall’ system which has positive effects regarding temperature and solar radiation falling on buildings. In urban areas the greening of walls ameliorate the inside thermal comfort of buildings and optimise landscape aesthetics. In rural areas the greening of livestock building walls should have the same positive impact as far as the thermal environment is concerned. The only problem might be the attraction of insects that are endemic mostly in rural areas.

Green walls allow the physical shading of the buildings, promote evapotranspiration during warm days and increase thermal insulation in summer. Schettini et al. [19] in an experiment carried out at the University of Bari tested three vertical walls, made up of perforated bricks, two of them covered with evergreen plants while the third was kept uncovered. In summer daylight temperatures were down to 9°C lower on shielded walls than those of the uncovered wall.

Conclusions
Food production systems of the future require more sustainable energy worldwide to support the growing population with food. What is necessary, is a protected environment for plant and animals inside structures such as greenhouses and livestock buildings so as to increase the agricultural
production, since the conditions are controlled. This is the reason for the continuously increasing number of agricultural structures.

Livestock buildings exist in order to provide animals with optimum growth conditions maintaining a thermal environment within the bounds of their thermoneutral zone. Heat stress in animals reduces dramatically their productivity e.g. milk production, weight gain, fertility etc. Therefore, farm buildings, like those in urban areas, need cooling systems and design techniques to decrease the inside temperature during hot periods. Conventional energy used by artificial cooling systems might not be economically viable as it also has negative effects on the environment. Consequently, passive cooling systems and design techniques support the sustainability of livestock buildings, positively affecting the viable development of animal production, which is a significant economic factor.

In this work, two categories of passive cooling systems and design techniques are described. The first one includes systems that have similarities with those used in residential buildings and are already used in livestock buildings. The second category includes urban systems that are applicable to livestock buildings and therefore are proposed to be adopted and adjusted.

The first group includes insulation, solar shading-shelters, orientation, building shape, roof inclination-colour and natural ventilation. The second one is comprised of earth integrated buildings wind catcher solutions, passive cooling roof in hot arid areas, earth to air heat exchanger combined with solar chimney and earth to air heat exchanger combined with wind tower.

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