Engineered solutions for animal heat stress abatement in livestock buildings.

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Abstract: Heat stress in animal housing is one of the drivers affecting animal productivity and welfare in hot climates, and causing consequent reduced profits for the farmers. The main challenges that livestock breeding faces in hot climates regards how to foster, improve, and assess methods and strategies for animal heat stress abatement. Research studies in this field have generally proposed modifications in herd management and in feeding strategies, breed selection, and engineered solutions aimed at exploiting heat transmission phenomena. In this paper, the most recent engineered solutions for animal heat stress abatement in livestock buildings have been reviewed and described; they have involved new building and ventilation design and modelling, and improved cooling systems and control. Results of this study have shown that two new concepts have been put forward; they concern the focus of the analyses on the animal occupied zone (AOZ) and the requirement of environmental homogeneity in the breeding environment for air supply and climate control. The engineered solutions described have all been recognised to have made important contributions to the development and assessment of novel heat stress abatement strategies for animals in livestock buildings. Finally, the analysis of these solutions allowed identification of the main issues in the field, to what extent they have been addressed and which issues should be object of further research.

Keywords: livestock housing, hot climate, ventilation design, cooling systems

1. Introduction

Livestock farming in hot climates is affected by a number of problems and difficulties arising from the need to cope with animal heat stress. This state, where an animal is responding to adverse hot conditions, induces adjustments, occurring from the sub-cellular to the whole animal level, to help it avoid physiological dysfunctions (Kadzere et al., 2002) as well as modifications of animal behavioural activities.

However, maintaining the animals in the zone of optimal well-being would be impracticable. Most of the efforts in farm animal management should be targeted in preventing the animals from entering the noxious stage beyond the zone of thermoneutrality. Therefore, when intensively housed animals are forced to live outside of their thermal comfort zone (TCZ), their behaviour and physiology will be negatively affected, and it is likely that production efficiency, welfare, health, value of the carcass, and reproductive capacity of animals will be reduced (CIGR, 2007).

In the tropical belt and arid areas, it is particularly true that the effect of heat stress is a major constraint on animal productivity, yet it is also substantial in the subtropical-Mediterranean zones, such as in central and western Spain, or in the southern areas of France, Italy and Greece. There, farm animals are exposed annually for 3–5 months to hot climates, high ambient temperatures, and considerable heat stress (Kadzere et al., 2002). Also in northern countries, heat stress is likely to become a serious risk factor causing increased mortality for intensive livestock (Turpenny et al., 2001).

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In general, the most severe heat stress is expected during the summer months because in many instances the temperature does not drop below 21°C at night. Conversely, if the temperature drops below 21°C for 3–6 h, the animal has sufficient opportunity to lose at night all the heat gained from the previous day (Igono et al., 1992; Muller et al., 1994).

The main challenges that livestock breeding faces in hot climates, and that scientist should investigate, were outlined during the workshop of II Section CIGR Working Group on ‘Animal housing in hot climates’, which was held in Catania (Italy) in 2005. They were subsequently summarised in a specific report (CIGR, 2006) and in the following meetings of the WG, which were held in 2007 in Cairo (Egypt) and in 2009 in Chongqing (China).

Some of these challenges regards ‘the investigation of various cooling methods’ (i.e., fans, fans and pads, sprinkling, fogging, etc.) to test their efficiency in terms of reducing heat stress, ‘the determination of design criteria for buildings (i.e., shape, orientation, thermo-physical properties of construction materials, ventilation opening efficiency, protection from sun load, etc.)’ (CIGR, 2006), and the need to ‘develop and improve advanced (PLF related) climate control technologies and create intelligent environmental control systems which will be able to predict and therefore control both the responses of the animals and the buildings in relation to the control interventions’ (CIGR, 2007).

During the recent years, a number of scientific research studies (Soldatos et al., 2005; van Wagenberg et al., 2005; Arcidiacono and D’Emilio, 2006; Cascone et al., 2006; Cruz et al., 2006; Huynh et al., 2006; Buscher et al., 2007; Haeussermann et al., 2007a, 2007b; Liberati and Zappavigna, 2007; van Caenegem, 2007, 2008; Liberati, 2008; Wang et al., 2008; Banhazi et al., 2009; Dagtekin, 2009; Norton et al., 2007, 2009, 2010; Rosmann & Buscher, 2010; Pang et al., 2011; Rosmann et al., 2011; Jeppsson & Botermans, 2014; Krommweh et al., 2014; Ortiz et al., 2015; Perano et al., 2015; Samer et al., 2015; Smith et al., 2015; Gebremedhin et al., 2016; Hempel et al., 2016; Mondaca and Choi, 2016; Vox et al., 2016) have proposed, analysed, and assessed engineered solutions to cope with animal heat stress in livestock housing. Their suitability for addressing the challenges that hot climates produce on farming activity should be thoroughly analysed.

This paper has specifically focussed on scientific research aimed at animal heat stress reduction in intensive breeding systems where animals, such as dairy cattle, pigs, sheep, and poultry, are kept in livestock buildings. It has not dealt with issues related to heat stress experienced by livestock kept outdoors in extensive breeding systems since the focus is on the engineered solutions for the design and assessment of the building and the equipment for animal breeding.

The main issues that have been addressed in these research studies were identified, solutions were analysed and compared, critical points highlighted and discussed, and conclusions on future research needed were delivered.

In the following Section 2, the housing solutions for heat stress reduction are analysed by comparing different building ventilation designs and modelling, and investigating material selection and optimisation of building geometry. Section 3 includes the description and comparison of the efficiency of various types of cooling systems in hot climates and the analysis of the evolution of cooling control models. Section 4 proposes the discussion on the findings of the previous analyses by highlighting the challenges addressed and the new concepts put forward. Finally, Section 5 presents the main conclusions drawn in the work and the future research that is needed to deal with the challenges still not addressed.

2. Housing solutions for heat stress reduction

As a premise, it should be underlined that differences in livestock housing solutions exist in dependence on the climate zone. The housing solutions in the tempered climate zone differ from those proposed in the subtropical and tropical zones. In the tempered zone, the animals are usually kept in enclosed insulated buildings with mechanical or natural ventilation whereas in subtropical and tropical zones the livestock buildings are generally open-sided and uninsulated (CIGR, 2006). For dairy cow housing, for instance, low-insulated roof, such as concrete, fibre-cement, aluminium or even local material (e.g., reed mats) are used.

Furthermore, economic development of the country affects the application of modern technologies and, as a consequence, differences exist among various areas in the world and even within the same country. On small farms, in fact, high investment costs and lack of investment capital may delay the modernisation of facilities (Samer, 2013).

In a recent survey, carried out in southern and central Italy on 943 barns (Peli et al., 2016), uninsulated roof covering was found in 64% of the structures. In naturally ventilated buildings, the lack of systems regulating the airflow rate was registered in 57% of the farms. In almost all of the remaining farms, the regulation was only manual and was not performed according to air temperature, air relative humidity, and/or wind speed. Where fan were supplied, the 66% of farms lacked an emergency automatic system in the event of electricity failure and in the 67% of the sample it was observed the lack of an alarm system for giving warning of the breakdown.

Based on these premises, since issues concerning animal heat stress reduction that are to deal with in the tempered climate zone are different if compared to those encountered in the subtropical zone, therefore related solutions should be adapted to the specific context.

In the following sub-sections, three aspects related to building geometry and material selection, design of naturally ventilated buildings, and the design of the ventilation system will be analysed.

2.1. Building geometry and material selection

In several research studies, the effectiveness of shade structures in hot climate (Swierstra & van Ouwerkerk, 1985; Moura & Naas, 2000) and the most important housing and management factors associated with sub-optimal thermal conditions (Banhazi et al., 2008) were identified by different approaches and statistical modelling. Significant factors resulted to be the building orientation and layout, as well as the need for innovative building designs (e.g., automated ridge vents, good quality roof insulation, steeper roof pitch, and smaller compartments).

Optimisation of building geometry has been focused in other studies that proposed steady state (Strom and Morsing, 2004) and dynamic modelling (Liberati and Zappavigna, 2007; Liberati, 2008) for building design. In these studies, roof geometry was found to be an important factor especially in uninsulated buildings since insulation makes thermal exchanges more uniform for the different building solutions. The increasing of eaves height, by reducing the view factor between the animal and the roof, reduces the thermal load to the animal during the day, but, on the other hand, also reduces that released from the animal during nighttime.

To the aim of minimizing the solar energy load and maximizing the heat discharge during the night, constructive solutions capable of maintaining the inside temperature as low as possible during all the day by satisfying these opposite requirements were designed and tested (Liberati et al., 2009). In this work, a ventilated roof was simulated to find out the optimal cooling conditions, i.e., the height of the ventilation duct of the ventilated roof able to minimize the internal building temperature, given the duct length and the air inlet velocity. The simulation was assessed in a reduced-model ventilated roof (Fig 1).

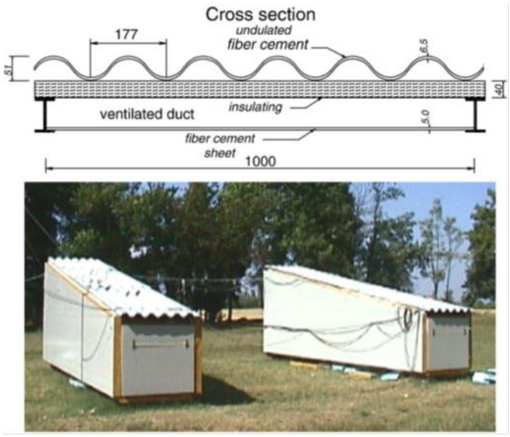

Fig. 1 - Experimental setup of the reduced-model ventilated roof (Source: Liberati at al., 2009)

The current research on building materials in hot climates has been aimed at reducing solar heat load on the building envelope. In a recent work (Vox et al., 2016), solar reflectivity and long wave infrared emissivity were evaluated by means of laboratory tests; the influence of the radiometric properties on the surface temperature was evaluated in the field by using an experimental structure.

Another research field regarding materials has included bedding material selection: the principle is that materials with high conductance may facilitate cooling of the animals. Practical applications of this principle already started two decades ago. From experiments with different bedding materials (wood shavings, sand, ground limestone, shredded paper and rubber mats), Cummins (1998) found that cows had highest preference for ground limestone which had the lowest temperature. As reported in Section 3.3, the idea of enhancing the heat transfer by conduction from the animal to the bedding has been developed in ‘conductive cooling’ systems for stall bedding.

When housed indoor, dairy sheep require an adequate ventilation regimen to maintain their thermal balance: 70 m^3/h/ewe can sustain ewe milk production (Sevi et al., 2002), whereas lower ventilation rates (35 m^3/h/ewe) have a detrimental impact on milk yield and quality, primarily due to a greater energy use for thermoregulation at the expense of milk synthesis, being feed intakes similar in the two cases (Sevi et al., 2003). Air hygiene in sheep houses can be positively influenced by a ventilation rate of 66 m^3/h per animal in summer and of 47 m^3/h per animal during the winter season. A smaller volume than 7 m^3/sheep may have detrimental effects on air, bedding and surface hygiene, increasing the susceptibility to subclinical mastitis (Caroprese, 2008).

Therefore, provision of a shade shelter is an essential measure to the welfare of farm animals in areas where typical ambient temperature during summer exceeds 24°C and THI exceeds 70 (Silanokove, 2000).

In this field, Hassanin et al. (1996) found that providing an asbestos shed for growing meat and wool sheep under Egyptian summer conditions reduced air temperature during daytime yet was insufficient to protect the animals from hyperthermia during the day and also the night, as it interfered with extra body heat dissipation to the surroundings during summer nights. They concluded that the construction materials for animal shelter during hot summer conditions are of extreme practical importance for animal protection against direct and indirect solar radiation in sub-tropical regions.

Further studies (Johnson, 1991; Sparke et al., 2001) found that a simple iron shelter is of little benefit to sheep in hot environments, because the hot iron sheeting will impose a long wave radiation load on the sheltered animals. Therefore, shaded areas need to be constructed to allow adequate airflow and using materials that will not absorb heat. They also suggested that wool length plays a role in the possible advantages of shading since they found that unshaded and shaded animals maintained similar body temperatures and respiratory rates with a wool length greater than 20 mm.

2.2. Naturally-ventilated building design

Naturally ventilation holds particular importance for the environmental control of animal houses in hot climates since it represents the most efficient method to modify air temperature and relative humidity levels and reduce the concentration of acidifying and greenhouse gases. An accurate design of a natural ventilation system should take into account specific factors of the livestock breeding environment, such as the layout of the building, the shape, size and position of the openings, the geometric features and position of the interior construction elements that might affect air flow, and the thermal gradients establishing within the building (Arcidiacono and D'Emilio, 2006).

Different measurements and modelling techniques, such as Computational Fluid Dynamics (CFD) and scale models, have been applied to analyse the effect of building orientation and vent geometry on temperature and air velocity inside naturally-ventilated livestock buildings.

De Paepe et al. (2012) analysed the effect of vent opening height by performing airflow measurements in and around 1:60 scale model cattle barns in a wind tunnel. They found that enlarging the inlet opening height led to lower velocities near the inlet, while higher velocities were measured at the outlet. The air velocities at the centre of the house were hardly affected by the inlet opening height, even with the front wall completely removed. Removing the outlet wall at the same time, however led to much higher velocities at the centre of the scale model (3-4 times higher).

Research in this field was carried out in hot climate conditions (Arcidiacono and D'Emilio, 2006; Cascone et al., 2006) by using CFD simulations and in-barn assessment through specific experimental tests. The aim of the first study was the analysis of the effects of building orientation on inside air temperature and velocity. Boundary conditions in the summer simulation were 27.6 °C, 860 Wm^{-2} radiation flux on a horizontal surface, 2.2 ms^{-1} wind speed at 10 m height. The simulated results showed that in summer the best ventilation at the animal level in the analysed barn and the lowest temperature were achieved when the ridge was W-E when the wind was from S-SE. The modification of the roof slope or the ridge vent did not have a significant effect on the simulation because the barn was a semi-open building. On the contrary, the presence of hay bales, which almost closed the windward opening, increased the velocity at the ridge vent (Cascone et al., 2006). In summer, the best ventilation and the lowest temperatures at the animal level in the analysed barn were found for wind direction perpendicular to the building or within ±45° (Arcidiacono and D'Emilio, 2006).

These outcomes find confirmation in a study by Norton et al. (2009), where ventilation effectiveness of a naturally ventilated livestock building, with eaves and ridge openings, under various wind incidences and with three different eave opening conditions, was investigated. Results of the simulations showed that when the wind was blowing normal to the building a considerable quantity of the flow left the building via 'short-circuiting' (Figures 2 and 3). However, the greatest ventilation homogeneity was experienced when the wind was blowing normal to the building, owing to the formation of two wind-driven vortices in the building. Results also showed that the highest level of environmental heterogeneity occurs at wind incidences of 10°÷40°.

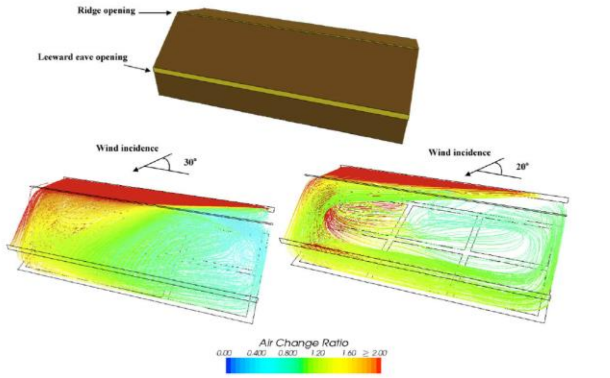

Fig. 2 - Airflow showing vortices at wind incidences of 20° and 30°, producing high levels of ventilation heterogeneity (Source: Norton et al., 2009)

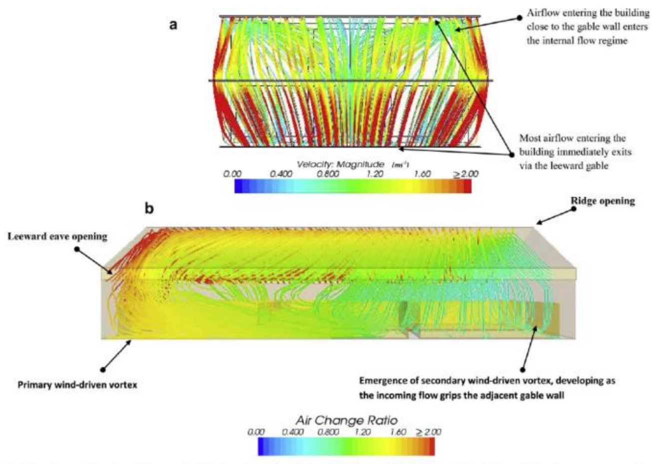

Fig. 3 - Airflow showing : a) short-circuiting effect at a wind incidence of 90°, producing the greatest ventilation homogeneity; b) two wind-driven vortices at a wind incidence of 60°, producing a lower ventilation homogeneity (Source: Norton et al., 2009)

Reduction of ventilation dead corners and the achievement of a uniform temperature within the barn are focal issues that influence also building design. In fact, due to the geometrical structure and ventilation configuration of naturally ventilated livestock buildings, the animal occupied zone (AOZ) can experience large heterogeneities in ventilation efficiency. Buildings geometrical features have a large bearing on the quality of the distributed indoor environment and therefore should be optimised to promote environmental homogeneity.

Therefore, it is desirable to know how to alter the geometrical features of a building in order to promote homogeneity in the indoor environment. In a later study (Norton et al., 2010), response surface methodology and computational fluid dynamics were used to develop predictive models that described the homogeneity of the indoor environment of a naturally ventilated livestock building as a function of its geometry and ventilation configuration. Three different eave opening conditions were chosen in order to improve the applicability of the developed response surfaces to practical situations. Results showed that for high to medium porosity eave opening conditions the environmental homogeneity was most sensitive to the building's roof pitch. However, when low porosity eave opening conditions were used the homogeneity was found to be highly sensitive to the sidewall height (Fig. 4).

In research studies regarding naturally ventilated animal houses, CFD has been applied without considering building surroundings so far. In a recent study (Hempel et al., 2016), simulations were performed for four wind directions and with or without surrounding buildings. CFD validation was performed with the measured data from a boundary layer wind tunnel under strictly controlled laboratory conditions taking into account full-scale measurement. The results showed that the simulated differences in air change per hour between wind directions can go up to 69% (without surroundings) and 77% (with surroundings). Neglecting the surroundings can lead to overestimation of the air change per hour with up to 41 %.

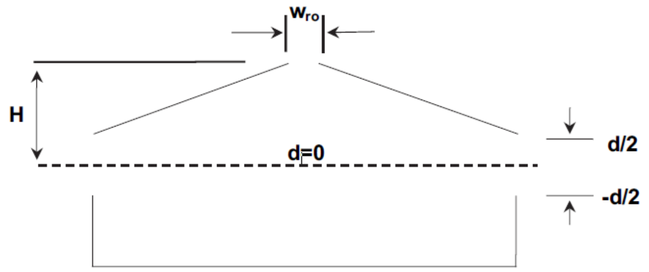

Fig. 4 - Building’s roof pitch and sidewall height of a livestock building (Source: Norton et al., 2010)

2.3. Ventilation system design and the Animal Occupied Zone (AOZ)

Since in livestock housing latent and sensible heat production is very high due to the high concentration of animals in the building, high values of airflow rate are required. Therefore, ventilation requirements are such that it is necessary to keep high values of airflow rate. This fact limits the applicability of some passive cooling strategies, and mechanical ventilation systems are used in most housing systems with different layouts, e.g., cross ventilation, tunnel ventilation, and pressure tube ventilation.

In this field, research has been focussed on the reduction of resource expenditure in order to reach the best microclimate conditions inside the building with a low conventional energy consumption during the summer period.

New housing solutions based on modular housing concept and integrating a geothermal heat exchanger (GHE) have recently been tested (Krommweh, Rosmann, Buscher, 2014; Rosmann, Buscher, 2010; Rosmann, Boge, Buscher, 2011; Buscher, Nannen, Schneider, 2007; Van Caenegem 2007, 2008). Differently from the earth-to-air heat exchanger (EAHE) systems (Ozgener, 2011), in commercial modular housing systems with integrated geothermal heat exchanger (GHE) no tubes are laid in the soil. The building has prefabricated slurry pits and walls, it is constructed on strip foundations, and it has highly insulated construction elements. The roof is covered with 0.05 m-thick sandwich panels, the animal section ceilings are made of 0.08 m- thick expanded polystyrene panels. The supply air is routed through a cavity between the soil and the slurry pit (Figures 5 and 6). Then supply air is led through a central corridor into the under-roof area and from there into the animal sections (Krommweh, Rosmann, Buscher, 2014; Rosmann, Buscher, 2010; Rosmann, Boge, Buscher, 2011; Buscher, Nannen, Schneider, 2007) or directly from the GHE cavity to the animal area (Van Caenegem 2007, 2008). In these studies, it was shown that this system has a great potential for saving energy and resources, though with high investment costs.

In one of the research studies on this system (Krommweh et al., 2014), almost 50% of the cooling quantity was provided in summer months, thus the authors concluded that the share of cooling hours of this modular housing in a warmer location could be greater, the higher the average outdoor temperature. However, there is the need to verify these conclusions in countries where average outdoor temperature exceeds that recorded in the experiments. On the other hand, only about two fifths of the cooling quantity provided by GHE reaches the sections. This fact shows that an increase of cooling quantity could be reached by a direct supply air ducting from the cavity (GHE area) into the animal section, similar to the ‘Krieger Systemstall’ analysed by Van Caenegem (2007, 2008), consequently the heating quantity would decrease in winter. The authors also concluded that further research is necessary to estimate the geothermal heat flow. In fact, in this study the heat quantity of the GHE included both transmission heat through the bottom of the slurry pit and geothermal heat flows whereby the corresponding proportions were not known.

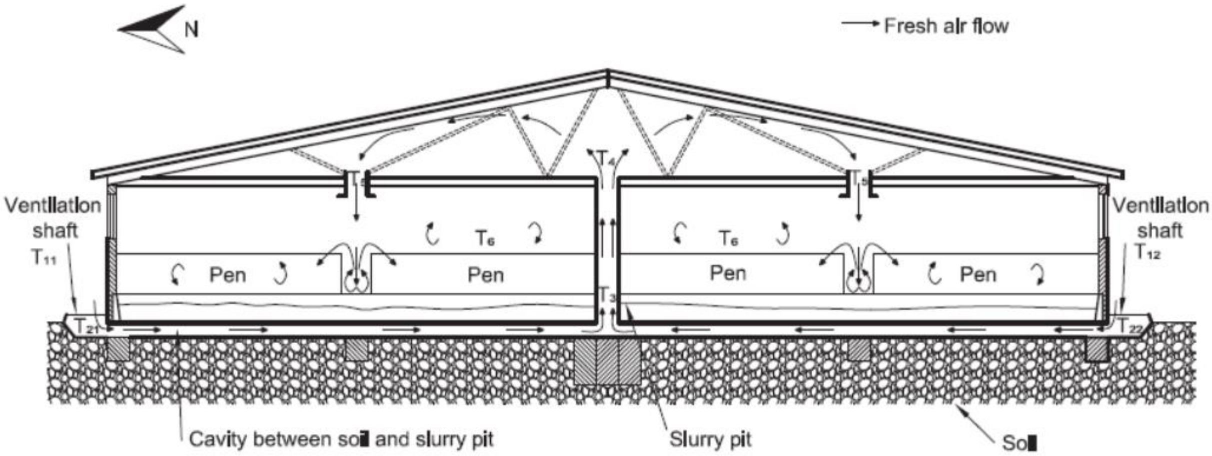

Fig. 5 - Modular housing with integrated GHE: supply-air flow and ventilation shafts. (Source: Krommweh et al., 2014)

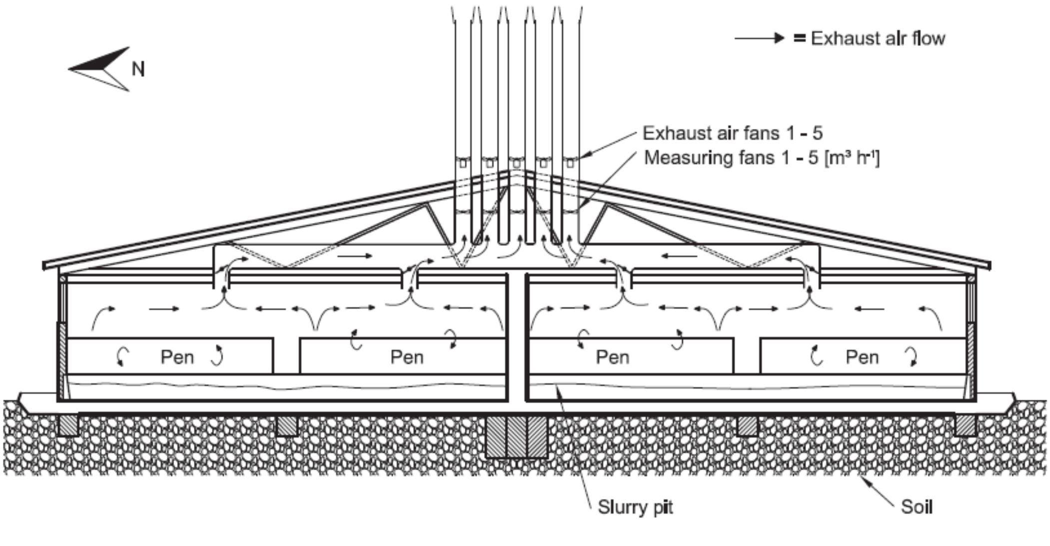

Fig. 6 - Modular housing with integrated GHE: exhaust-air flow and fans. (Source: Krommweh et al., 2014)

Another example of energy saving ventilation system involves the distribution of the fresh incoming air through ground channels (Fig. 7) close to the animal occupied zone (AOZ) to improve the ventilation efficiency and be able to reduce the ventilation rate through the building without worsening the animal aerial environment (Van Wagenberg et al., 2005).

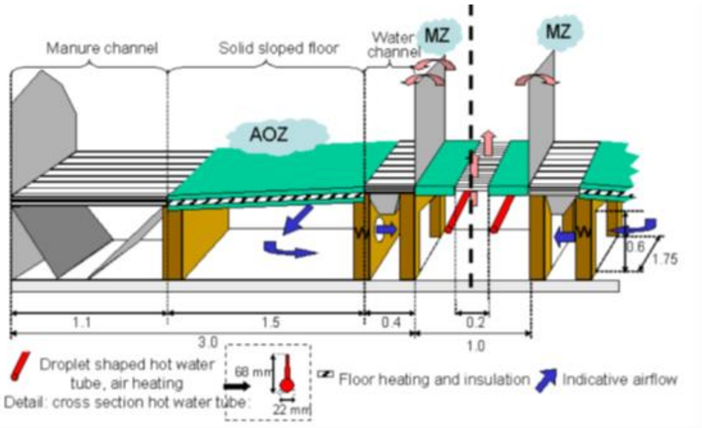

Fig. 7 – Example of Ground channel ventilation (Source: Van Wagenberg et al., 2005)

Ground channel ventilation (GCV) is a relatively new ventilation design that uses underground air supply channels to deliver fresh incoming air by displacement airflow directly to the animal occupied zone (AOZ) through slatted floor inlets. Despite the growing popularity in GCV designs at a commercial level, limited studies have been carried out to fully characterise the indoor air distribution and the underground air supply channels.

With a different aim, concerning the analysis of dust and ammonia releases in the indoor breeding environment, Jeppsson & Botermans (2014) considered three different combinations of negative pressure ventilation systems with GCV. The three systems described in Figure 8 were: A: High exhaust ventilation with air inlets in the ceiling (Conventional system) B: High exhaust ventilation with incoming air close to the animal occupied zone through ground channels. C: Combined high (75% of max ventilation rate) and low exhaust (25% of max ventilation rate) ventilation with incoming air close to the AOZ through ground channels. Results showed that ventilation system B increases the ammonia concentration in the workers breathing zone compared with ventilation system A. The ventilation system C had the lowest ammonia concentration in the workers breathing zone.

The topic is still object of current research, as found in a recent review (Zagorska, 2012).

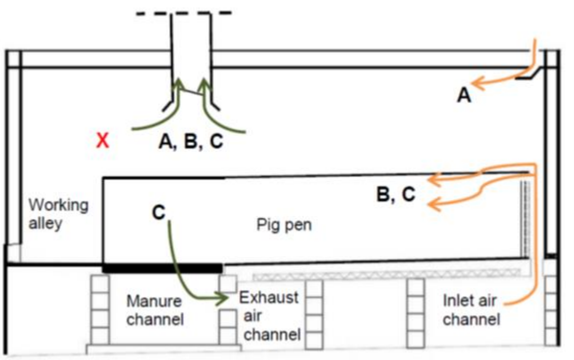

Fig. 8 - Combination of negative pressure ventilation systems. A: High exhaust ventilation with air inlets in the ceiling (Conventional system). B: High exhaust ventilation with incoming air close to the animal occupied zone through ground channels. C: Combined high (75% of max ventilation rate) and low exhaust (25% of max ventilation rate) ventilation with incoming air close to the AOZ through ground channels. (Source: Jeppsson and Botermans, 2014)

3. Cooling in hot climates

During the summer season, the highest airflow rates are needed inside livestock houses. At the same time the difference between the inside and the outside air temperatures is very small and, in the absence of wind, the natural ventilation is insufficient.

In hot climates, the potential for non-evaporative heat loss is reduced and animals rely on evaporation of water to dissipate any excess heat generated by metabolism.

In the next sub-sections the use of evaporative cooling in hot and humid climates, the advantages and disadvantages of fogging systems compared to surface wetting and spray cooling, novel conductive and radiative cooling systems, and the evolution of cooling control systems will be analysed.

3.1. Efficiency of Evaporative Cooling in hot and humid climates

Evaporative cooling is an adiabatic humidification process that decreases the air temperature by the evaporation of water in the air stream. In this process, sensible heat is converted into latent heat, resulting in a reduction in the dry bulb temperature and an increase in the relative humidity of the air. When evaporating water into the air, also conduction increases because thermal conductivity of water (0.5918 $Wm^{-1}K^{-1}$) is about 22 times higher than air one (0.026 $Wm^{-1}K^{-1}$) at 290 K.

Much research work has shown that evaporative cooling is more efficient in the regions with a high air temperature and low relative humidity, i.e., characterised by hot and dry summers (Fig. 9). However, little information is available on the suitability of an evaporative pad cooling system to the regions with humid and hot climates. Even in regions where the weather is generally perceived as warm and humid, the hottest part of day is likely associated with relatively low humidity, hence presenting the opportunity for cooling with the pad-and-fan system. Wang et al. (2008) evaluated the suitability of an evaporative pad cooling system in poultry houses to the summer climate by using a fuzzy mathematical method to analyse 20-year’s weather data from nine representative cities with various climates in China. The results of the evaluation showed that the average air temperature inside poultry houses could be lowered below 28 °C by using the evaporative pad cooling system for over 65% of the days in one hot season for Beijing, Xi’an and Jinan, while the temperature of about 70% of the days could be controlled to below 30 °C for the remaining cities.

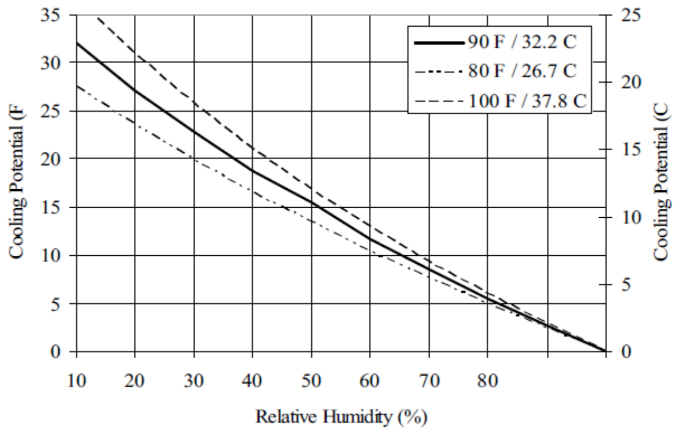

Fig. 9 - Cooling potential in dependence on the air temperature and relative humidity (Source: Harner et al., 2009).

Evaporative pad cooling systems have been used in humid environments to decrease the air temperature in tunnel-ventilated facilities (Liao and Chiu, 2002). On the other hand, limited information is available on the use of evaporative pads in cross-ventilated free-stall facilities in humid environments. Results from a trial (Smith et al., 2015) showed that even under mild heat stress, evaporative cooling in cross-ventilated facilities can decrease core body temperatures of cows and tended to increase their lying time. Additional work under more severe heat stress conditions is recommended to evaluate effects of cow cooling on lying time.

The efficiency of evaporative pad cooling systems can reach over 80% in hot and dry conditions (Timmons and Baughman, 1984; Kittas et al., 2003). For example, in broiler buildings located in the southwest of Portugal during the summer of 1998, Cruz et al. (2006) found that air temperature was reduced from 39 °C to 27 °C by an evaporative pad cooling system.

A later research (Dagtekin, 2009), carried out in a typical poultry house, aimed at investigating the performance characteristics of evaporative pad cooling systems for the Mediterranean region of Turkey. Average evaporative cooling efficiency ranged from 69.2% on July 18, to 72.0% on August 3. The temperature decrease in pad exit during the experiment was between 7.3 °C, and 4.4 °C.

To enhance evaporative cooling pads efficiency, desiccant materials was tested by applying it before and after the pads (Samer et al., 2015). The hypothesis is that desiccant segments absorb air moisture before introducing the air into the pads, thus the treated air is able to absorb more moisture from the cooling pads. The results showed that the desiccant materials are suitable to absorb moisture from air in dynamic motion. The adsorption capacity depends on the starting conditions (temperature, relative humidity, ventilation rate) and attains its half value after 150 min, fand then the desiccant material should be reactivated.

Cooling systems that are used to reduce heat stress in livestock buildings require high energy and water usage. When there are increases in electricity costs and/or reduction of water availability there is the need for improved performance of cooling systems.

Research in this field (Panagakis and Axaopoulos, 2006 and 2008) aimed at finding the fogging strategy suitable to obtain results that are comparable to those achieved by evaporative pads. The 'Same duration of heat-stress as when using evaporative pads' strategy was more efficient than 'same intensity of heat-stress as when using evaporative pads' strategy though larger water quantities are needed.

To provide stable and desired supplying air temperature for varied airflow rates, required in different production stages by using on-off wet pad cooling, a study (Rong et al., 2016) investigated the dynamic performance of evaporative pads under different air speed and various running time of the pump in a cycle time of 4 min. It was found that outlet air temperature descends slightly with higher air speed and decreases with larger on-time, especially when on-time is 10, 20 and 30 s.

Steady-state model based on psycrometric relations of the evaporative cooling process, and balance equations of latent and sensible heat were used for deriving parametric charts (Arcidiacono, 2006). The application of the model to a commercial piggery showed that there was the need of improving building insulation, the animal being out of the

'Production space', and allowed to assess the effectiveness of two farrowing rooms having different air inlets. The ceiling with diffuse air inlets was found to improve the room microclimate compared to the use of direct inlets.

Test of supplementary air inlets during summer time in a farrowing unit with diffuse air inlet (Joergensen et al., 2016) demonstrated that air quality was improved at sows with supplementary air inlets and the best conditions were achieved when the air stream was lead directly to the sow in each pen.

In positive pressure tube ventilation systems (Figures 10 and 11), perforations on the tube were optimized using CFD simulations to create air jets targeted at specific areas of the animal (rather than the entire barn) and were assessed in an experimental test (Mondaca and Choi, 2016) . The results showed that the jets do not produce a symmetrical pattern despite the symmetry of the tube, which is a phenomenon primarily due to the counter clock-wise swirl effect of fans. This effect influences the patterns produced by the first few sets of jets while the patterns produced by the last 5-6 sets are consistent, since the back-pressure eliminated the swirl effects.

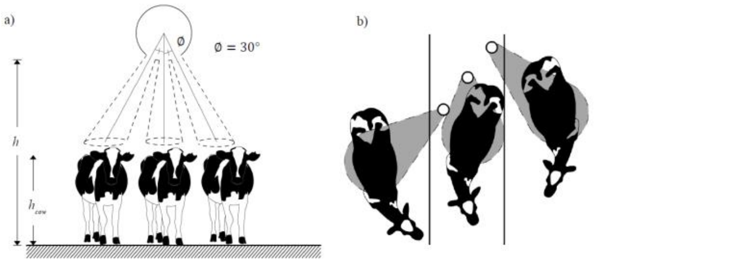

Fig. 10 - Pressure tube ventilation system: a) targeted cooling for dairy cows; b) top view of air jets' discharge (Source: Mondaca and Choi, 2016)

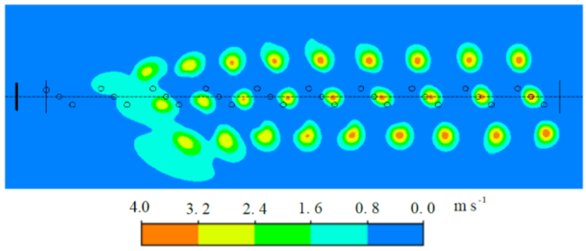

Fig. 11 - Pressure tube ventilation system: velocity contours at 1.5 m height from the floor, by using CFD simulations.

3.2. Fogging systems versus surface wetting and spray cooling

Pad-and-fan or high-pressure fogging cools the animals by lowering the air temperature. In contrast, surface wetting attempts to cool the animals directly without markedly altering the ambient environment. Compared with pad-and-fan or fogging system, surface wetting uses much less water (less than one-fourth) and keeps the air drier. It also offers a better potential to cool the animals under hot/humid conditions where effectiveness of pad-and-fan or fog cooling would be more limited. Tao and Xin (2003) performed an extensive laboratory-scale study to quantify the impact of surface wetting on market-size broilers under various temperature, humidity and air velocity conditions.

Spray cooling of grower pigs demonstrated that a 5.8% increase in daily feed intake, a 4.5% improvement in feed conversion and an 11.2% increase ($p<0.05$) in average daily gain could be achieved on Australian pig farms (Banhazi et al., 2009).

Cooling a solid floor during hot periods in the summer improves the feed intake and daily gain (Bull *et al.*, 1997; Eigenberg *et al.*, 2002; Huynh *et al.*, 2006; Lucas *et al.*, 2000). The cool floor also improves the lying behaviour: more pigs choose to lie on the cool solid floor instead of the slatted floor (Huynh *et al.*, 2004, 2005; Barbari and Conti, 2009).

It is essential, and economically justifiable, to install well-controlled sprinkling systems in piggery buildings (Lucas *et al.*, 2000). The amount of water required is about 330 ml per pig per hour for spray cooling dry sows, boars, growers and finishers, and drip cooling of sows. For weaners, 65 ml per hour is recommended. A typical spray cycle for growers and finisher pigs would be five minutes spraying followed by a 45 minute delay. Adequate ventilation is essential for drip and spray cooling to be effective. A minimum air speed of 0.2 metres per second at pig level is essential, but there is no advantage in exceeding 1.0 metre per second. Too much air movement can chill even fully-grown pigs (Hahn *et al.*, 1987; Riskowski *et al.*, 1990). Therefore, it is important that only part of the pen area is under sprays, so pigs can choose to stay dry, as the animal itself is the best sensor of heat stress. Spray cooling is also viable cooling method for poultry (Tao and Xin, 2003) and has been shown to positively influence egg production (Ikeguchi and Xin, 2001; Xin and Puma, 2001).

The alternate activation of a fogging system associated with forced ventilation installed in the resting area and a sprinkler system associated with forced ventilation installed in the feeding area of a free-stall barn for dairy cows was found effective for encouraging the decubitus of animals in the stalls (D'Emilio et al., 2017).

3.3. Conductive and radiative cooling systems

Conductive cooling is an alternative method of cooling dairy cows, which will work effectively under humid conditions and could be complementary to existing systems. Conductive cooling, which is based on direct contact between a cow lying down and a cooled surface (water mattress, or any other heat exchanger embedded under the bedding), allows heat transfer from the cow to the cooled surface. Conductive cooling has the potential to conserve water (by recycling all the water as a working fluid in a closed-loop system) and may require less energy than evaporative cooling units. Conductive cooling may also improve animal hygiene and reduce humidity in the barn compared to evaporative cooling systems. Recent work has been done in the USA (Ortiz et al., 2015; Perano et al., 2015; Gebremedhin et al., 2016) to model and assess this kind of systems. A study was conducted to evaluate the use of conductive system for cooling cows, composed of heat exchangers buried 25 cm below the surface of the beds that were filled by either sand or dried manure (Ortiz, et al, 2015). Sand was found to be superior to dried manure as a bedding material for the use of heat exchangers. They concluded that use of heat exchangers is a viable adjunct to other systems that employ fans, misters, and evaporative cooling methods to mitigate effects of heat stress on dairy cows. Extensive experimental tests (Perano et al., 2015) proved that water mattresses are effective for increasing cow's production (Fig. 12). Modelling conductive cooling by CFD and 3D mathematical model of conduction between cow and water mattress (Gebremedhin et al., 2016) showed that key factors are water temperature, air temperature, and skin wetness (Fig. 13). A patented cow bedding heat exchanger was recently designed and assessed (Choi et al., 2014).

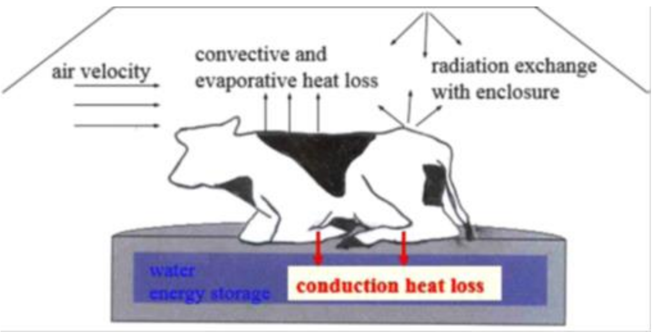

Fig. 12 - Heat loss from cow bedding heat exchanger (Source: Gebremedhin et al., 2016)

In another approach to conductive cooling modelling (Radon et al., 2014), the finite volume technique has been applied in the calculation model to determine temperature patterns and heat flows. In this method, the conductive area is divided into small balance-differential elements where heat accumulation and exchange with neighboring elements occur. The results showed that heat loss is highest at the beginning of lying bout, then decreases with time. In case of poor thermal insulated bedding, shorter lying breaks reduces heat loss significantly. Based on additional calculations assuming various lying time patterns it could be roughly estimated, that lying breaks shorter by 0.5 h reduce maximal heat loss of about 50–80W in winter and 15–30W in summer for sand bedding.

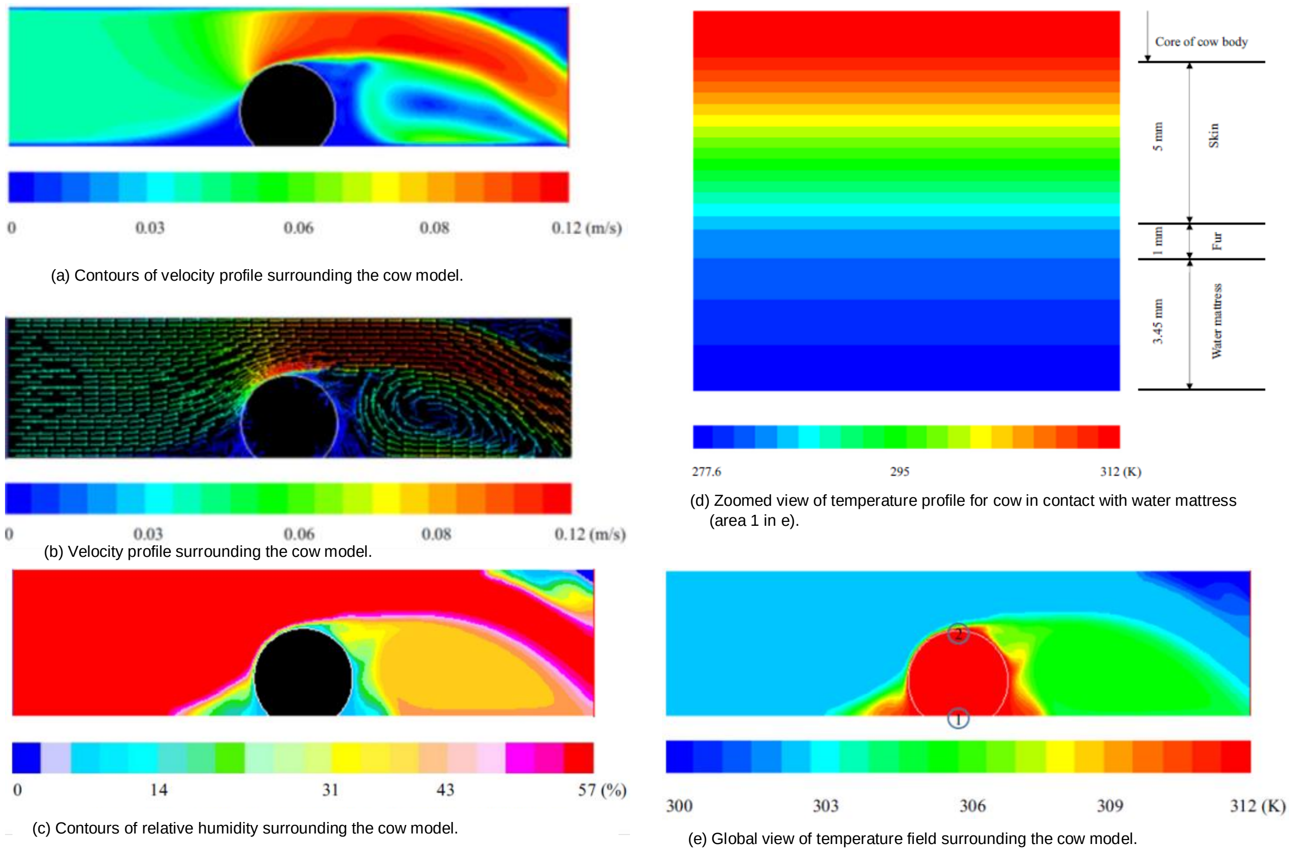

Fig. 13 – Contours of velocity profile, temperature and relative humidity surrounding the model cow, and views of velocity and temperature profiles. (Source: Gebremedhin et al., 2016)

Another alternative method to ventilation is the use of ‘radiative cooling’ (Fig. 14). In this field, a water-cooled cover (WCC) for sows’ stalls was assessed in a recent work (Pang et al., 2011). Increasing water flow rate (from a well) through the WCC up to 4 l/min enhanced cooling efficiency whereas, beyond this value of flow rate, little additional benefit could be gained. In further studies, the authors would include the development of an intelligent control system for operating the WCC to optimise the system performance while conserving water and energy.

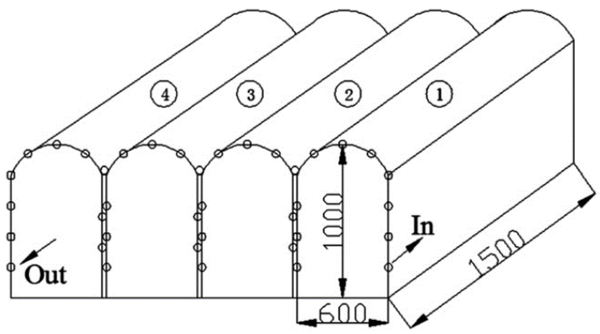

Fig. 14 - Representation of the water-cooled cover for sow's stalls (Source: Pang et al., 2011)

3.4. Cooling control

The analysis of literature showed that climate control models evolved from simple control systems based on maximum and minimum limits, to model-based climate control systems and, further, to combined climate control systems, and from steady state simulation models to dynamic models (Axaopoulos et al., 1992; Zhang et al., 1992, 1995; Chao et al., 1992). In the early model-based climate control systems, simulations were conducted under the hypothesis of perfectly mixed ventilated space; furthermore, no validation under real field conditions was carried out. The work of other researchers (Daskalov, 1997; 2005, 2006; Soldatos et al., 2005) regarded the implementation of dynamic auto-regressive moving average models, adaptive systems, and robust nonlinear feedback control in conjunction with feed-forward action. Gates et al., (2001) incorporated a fuzzy logic-based controller method to improve existing staged ventilation control systems. However, in all the above-mentioned models no dynamic responses of animal heat and moisture production were considered.

More recently, based on the work of Berckmans et al. (1992), combined models were defined (van Wagenberg et al., 2005; Haeussermann et al., 2007a, 2007b). In these models, more knowledge about the interaction between the animal responses (e.g. heat production) and the control actions was integrated into the applied control algorithms. In fact, due to the dynamic changes of inputs (animal heat production, ventilation rate, cooling rate, etc.) and disturbing factors (outdoor climate), the calculated indoor conditions rapidly change over time. In these studies, a data-based model, developed from measurements of adiabatic indoor air cooling by fogging with fine water droplets, was integrated in a dynamic mechanistic simulation model of energy and mass transport. The combined simulation model allowed the simulation of indoor air temperature, indoor humidity, and ventilation rate.

An accurate control of high-pressure fogging systems can either be reached by varying the supplied water amount, hence evaporation rate, or by varying the ventilation rate (Gates et al., 1991; Arbel et al., 2003). Notwithstanding, the effective evaporative fraction and evaporation rate depend on several factors and can vary considerably among different housing systems.

In order to improve the control of a fogging system, information on evaporation characteristics of the specific system is needed and it can be used either for an accurate on-line control or for simulating optimized control settings. In a study carried out in a mechanically ventilated research facility for pigs (Haeussermann et al., 2007a, 2007b), two objectives were achieved: (1) to investigate effects of a high-pressure fogging system on inside air temperature and relative humidity, ventilation rate, water consumption and energy use, and average daily weight gain of the pigs, during year-round measurements; (2) to model the evaporation process and estimate main influencing variables on evaporation characteristics, such as evaporative fraction (EF) and time constant for reaching steady state (tSS). EF and tSS were influenced largely by temperature and saturation deficit. While the EF was 100% during steady state, and 63% of steady state was reached within 65 s during warm and dry ambient conditions (28 °C; 53% RH), the EF dropped to 89% and 65% for moderate (21 °C; 69% RH) and cold/humid (13 °C; 83% RH) indoor conditions, respectively, and the time tSS to reach steady state was nearly doubled for the latter. Average reduction of diurnal peaks in indoor temperature was about 4 to 5 °C.

As the control of fogging systems is based on the knowledge about the evaporation rate (Gates et al., 1991), the information about the evaporative fraction b and the time needed to reach steady-state conditions (t63: time constant for reaching 63% of steady state, in seconds) is one of the main input factors. Commonly, b is assumed to be 100% if model based investigations on fogging system are performed (Panagakis et al., 1996; Arbel et al., 2003). This might be correct for hot and dry climatic outside conditions but has to be restricted for moderate climates.

Also in cooling control systems the focus on AOZ was considered in the literature. Several researchers (Van Wagenberg and Smolders, 2003; Van Wagenberg and de Leeuw, 2003; Van Wagenberg et al., 2004) started to focus on AOZ climate control instead of room climate control. There are practical reasons for positioning the temperature sensor for climate control outside the AOZ, yet significant temperature differences can occur between the sensor position for climate control and the AOZ (van Wagenberg et al., 2005). The position of the sensor in the AOZ has to be carefully considered, because animals close to the sensor influence the measurement. Furthermore, the use of a model–based predictive (MBP) controller instead of a conventional controller was found useful, because an MBP controller takes action based on the calculated future behaviour of the system, based on a model of the system.

4. Discussion

The engineered solutions above described have all made important contributions to the development and assessment of novel heat stress abatement strategies for animals in livestock buildings.

The analysis of the advances in scientific research on animal heat stress abatement strategies, with specific focus on the engineering aspects, has shown that:

- Housing solutions for heat stress reduction included new modelling approaches for building and ventilation design, which specifically regarded optimisation of building geometry, natural ventilation design by CFD modelling, and the assessment of novel facilities, which encompassed modular housing, novel ventilation design, and passive cooling systems. However, some of the solutions display certain limitations that regards the assessment in real hot climates. For instance, in commercial modular housing systems with integrated geothermal heat exchanger (GHE), it was recognised that there is the need to verify the hypotheses done. Further research is thus needed to assess these housing solutions in different hot climate countries. Experimental validation, in laboratory and in full scale, is necessary also for CFD simulations to ensure that those simulations are more than just theoretical exercises (Norton et al., 2007). Moreover, some assumptions in CFD modelling, such as that of uniform animal presence, need to be overcome and the partitioning of animal heat flux into sensible and latent is necessary to interact with climate control models.

- Two new concepts have been put forward, i.e., the focus of the researches switched from the room, or the confined environment, to and Animal Occupied Zone (AOZ), and highlighted the requirement of environmental homogeneity in the breeding environment as a challenge for research, for both air supply and climate control.
- The challenge of reducing the use of water and electricity has been faced by: i) the use of passive cooling systems, such as GHE and GCV; ii) the improvement of ventilation efficiency, such as with the optimisation of Positive pressure tube ventilation systems, and iii) the enhancement of cooling performance through the modelling and validation of different Conductive cooling systems, the design and assessment of Water-cooled cover (WCC) for sows in hot humid climate, and the investigation on the suitability and performance of Evaporative cooling systems.
- Climate control for heat stress reduction modified from simple control systems based on maximum and minimum limits to model-based climate control systems, and further on to combined climate control models in order to include dynamic responses of animal heat and moisture production. The control system should be operated not only in dependence on environmental conditions but also on the animal conditions. Since energy expenditure is a function of the setpoint T and ventilation rate (which depend on target relative humidity and aerial contaminants), thus, it would be adequate to use sensors of animal presence to operate cooling systems just when the animal needs it physiologically, and it would avoid losing water. Inevitably, these hints arise problems of thermoneutral zone (TNZ) definition, and requirements related to the use of non-invasive low-cost sensor technology.

The potentially important role that modelling could play in improving livestock productivity, sustainability, and efficiency is still not thoroughly captured by any of the solution reviewed. Therefore, it would be valuable to design, evaluate and optimise climate systems, taking into account both technical performance and costs. It would also be relevant to quantify the importance of staying within the TNZ and determine the costs of exceeding this zone due to less efficient production. Since there is an individual response of animals within the same breeding environment, as highlighted in PLF principles (Berckmans, 2004), it could be of interest to define the difference between the needs of the average animal and those of the weakest. This information would be useful for predicting economic losses or benefits of alternative environmental management strategies, arising from temporal variations in microclimatic parameters.

In light of these challenges, one promising trend over the past two decades has been the substantial growth in the coverage and adoption of information and communication technologies (ICTs). However, change in technology and housing materials have modified the animal breeding environment while genetic selection (especially in cows and pigs) may have affected animal thermoregulatory capability in hot climate and how they cope with heat stress (Brown-Brandl et al., 2004; Hayes et al., 2013). Thus, more research is needed in the field of animal thermoregulation in relation to housing facilities and cooling systems.

5. Conclusions

A review of research studies has been presented in this paper with special focus on the engineered solutions for animal heat stress abatement in livestock buildings. This study has identified a number of key aspects that have been considered in the recent literature. Among them, the optimisation of building design and material selection was carried out to exploit heat transmission phenomena (radiation, convection, and conduction). In naturally ventilated animal houses, Computational fluid dynamics (CFD) has widely been applied to simulate different building or vent geometries in order to assess environmental homogeneity in the building. Moreover, new ventilation system has been proposed and assessed, with focus on system performance and CFD modelling hypotheses in the animal occupied zone (AOZ). The challenge of reducing the use of water and electricity has been addressed by proposing different solutions.

The major concerns are related to the fact that some of the solutions proposed are too complex to implement and require major technical support. This is not suitable especially for application in low-income countries or economically depressed areas of a country, especially if a high cost is required. Adaptation of solutions on large scale requires the development of low cost systems and robust models.

Several research works attempt to present a multidisciplinary approach yet the small or sometimes unavailable link among multidisciplinary solutions reduces the impact of several researches. From one hand, partial solutions should be supported with comprehensive details of other compatible procedures that could make the intended solution complete while, from the other hand, further work is required to overcome a certain lack of generalised solution to different problems. For instance, the need to focus on the AOZ (modification of the animal microclimate) and/or the different thermal requirements (e.g., piglets and sow) imply that further research on localised cooling should be carried out at a multidisciplinary level. Reduction of water and energy consumption needs would require further research on control systems to optimise their performance while conserving water and energy.

Since the combination of high temperatures and high relative humidity (RH) resulting in heat stress remains one of the major problems that affects the production efficiency and welfare of livestock animals in tropical and subtropical regions, future research work should foster collaboration of the different working groups acting in different scientific domains for a common challenge. Therefore, a broader holistic perspective should be considered, which also encompasses physiology and behavior, and a more tight connection between scientists having complementary competences would be beneficial.

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