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Energy-saving ventilation system for sheep premises to ensure food security and safety

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Abstract

The impact of stress on an animal's physiological and behavioral state and the final meat quality has been extensively established. Prior to slaughter, animals are usually denied food and drink to reduce stomach content and minimize contamination from gut contents spilling from unintentional punctures to the gastrointestinal system during the eviscerating procedure. Feed withholding offers the benefit of lowering consumption of food as well as morbidity and death rates while in transit. Food restriction, on the other hand, triggers a stress reaction and causes animals to lose weight. In sheep farming, ventilation systems that functioned at temperatures above the threshold air temperature and relative humidity were very efficient and productive. The ventilation system proposed here works by using soil warmth, i.e., a renewable source of energy, and contributes to environmental protection. The results of theoretical and experimental studies of an energy-saving ventilation system using soil heat are presented. The use of an energy-saving ventilation system reduces energy and labor costs for creating a microclimate in sheep premises. The device of an energy-saving ventilation system is protected by the patent of RK KZ 26930 dated 15.07.2016.

Keywords: food security and safety; underground heat exchanger; air duct; soil heat.

Practical application: It is used to create a microclimate in a sheep-breeding room.

1 Introduction

Sheep are a vital source of income for local farmers and landless people in rural areas. It emphasizes the possible influence of sheep ranching management on food security and safety concerns in particular areas (Rice et al., 2020; Soni et al., 2021; Warriss, 2020). The significant connection of sheep with the environment in rural and extended agricultural systems renders sediments, air, and environmental quality of soils connected to water supply a critical component in ensuring a secure and safe alimentary intake of sheep-derived foods. Food derived from animals is the primary source of exposure for the common people to persistent organic pollutants, including polychlorobiphenyls and dioxins, as defined by the Stockholm Convention, which was developed with the UN Environment Program's assistance (Grandin, 2021; Leonte & Leonte, 2020; Onopiuk et al., 2021). The muscles of animals (as well as humans) contain a sugar called glycogen, which is converted to lactic acid after death. This is what makes meat crispy, tasty, and also resistant to bacteria. When an animal is stressed, for example, scared, tired, or sick, muscle glycogen levels drop and it is spent on metabolism, energy supply, and coping with stress. Therefore, the lactic acid level of this animal after slaughter is significantly lower than other healthy animals. This is the same change that occurs in the slaughter of old and malnourished animals, malnourished animals, sick animals, high stress of animals slaughtered at home, and violent treatment of animals before slaughter or harassment. Furthermore, recent research has discovered that food restriction has relatively little influence on meat quality characteristics (Table 1) (Baljić et al., 2019; Costa et al., 2020; Gali et al., 2020; Stahlke et al., 2019).

Rational use of fuel and energy resources is one of the world's global problems today. One of the promising ways to solve this problem is the use of new energy-saving technologies using non-traditional renewable energy sources (Ponnampalam et al., 2020; Tsakiridis et al., 2020). The range of renewable energy sources applications on farms is quite wide: this includes heating or cooling buildings, drying agricultural products, desalination or heating water, and even autonomous energy supply.

The advantages of such energy sources are environmental cleanliness and low labor and money costs for the operation of installations for their use. The solution to the problem of energy saving in agricultural ventilation systems is the effective use of low-potential soil heat (Phillips, 2019). The soil of the surface layers of the Earth is actually a thermal accumulator of unlimited capacity, the thermal regime of which is formed under the influence of solar radiation. The low-potential heat of the Earth can be used in agricultural premises for heating, hot water supply, air conditioning (cooling) (Nenadović et al., 2021).

There are a number of examples of the use of soil heat for heating and cooling livestock premises through underground air ducts and heat exchangers. They have saved from 50% to 75% of the cost of heating and cooling the premises. The study of these examples allowed to development of an energy-saving ventilation system for sheep premises (Ibidhi & Salem, 2019; Moberg et al., 2021). Figure 1 shows the functional scheme of the ventilation system; Figure 2 - section on A-A of Figure 1; Figure 3 - block scheme of the control of the electric motor and control valves of the supply air ducts and air funnel, spray, and closers.

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Table 1. The impact of pre-slaughter management on animal stress responses and meat quality characteristics has recently been published.

Factor	Carcass and meat quality traits	Stress responses	Species	Pre slaughter handling conditions
Food/water deprivation	12 and 24 h food deprivation increased muscle $pH_{3\,h}$ and $pH_{24\,h}$; sarcomere length increased at postmortem 0 h, while decreased at postmortem 10 h after 24 h fasting	24 h food deprivation increased plasma corticosterone level	Poultry	0, 12, and 24 h food deprivation
	Pigs deprived of food for 24 h had lower carcass dressing yield; 14 and 24 h food deprivation increased carcass bruise score; food deprivation had limited effects on meat quality traits	14 h food deprivation-induced the highest urinary cortisol level	Pigs	4, 14, and 24 h food deprivation
	Water deprivation caused an increase in live weight loss; water deprivation decreased drip loss, cooking loss, L^*, b^*, and ultimate pH	Water deprivation increased urea, creatinine, and muscle supernatant osmolality	Sheep	48 h water deprivation or not under normal or high ambient air temperature
Transport	Transport decreased live body weight; transport increased ultimate pH and shear force value, while decreased expressed juice, cooking loss, sarcomere length, and meat color (L^*, a^*, and b^*) values	Transport increased plasma cortisol, dopamine, adrenaline, and noradrenaline levels	Sheep	48 h lairage with *ad libitum* feed and water as a not-transported group; 2 h preslaughter transport under high temperature (37.5 °C) as transported group
	Transport time significantly affected drip loss, pH, and meat color	3 h transport elevated plasma glucose and lactate levels; 5 h transport elevated plasma cortisol, LDH, and glucose levels	Pigs	40 min compared with 3 h compared with 5 h transport
	2 h or longer transport caused the morality of broilers; 0.5 h transport decreased pH, increased lightness, drip loss, and cooking loss, inducing PSE-like meat	Transport increased plasma CK and LDH levels	Poultry	Unstressed control compared with 0.5 h compared with 1 h compared with 2 h compared with 4 h transport; high temperature (40 to 42 °C)
Lairage	Lairage increased weight losses; 3 h lairage induced the highest pH, shear force, and toughness and the lowest b^* and chroma values; 3 and 6 h lairage decreased WHC at 24 h post mortem; the effects of lairage time on texture and WHC disappeared after 5 d storage	–	Sheep	1.5 h preslaughter transport followed by 0, 3, 6, and 12 h lairage
	1 h rest reduced muscle temperatures; 3 h rest normalized early postmortem pH decline; 1 or 3 h rest decreased drip loss and extra-myofibrillar water; rest had no effect on toughness	–	Pigs	Treadmill exercise followed by 0, 1, or 3 h rest
	Lairage decreased ultimate pH; Bulls subjected to 24 h lairage had the lowest L^*, b^*, and H^* values; lairage time had no effects on WHC, cooking loss, and shear force values	–	Cattle	30 h preslaughter transport followed by 24, 48, and 72 h lairage
Transport and lairage	Transport, lairage, or transport × lairage had no effect on pH, drip loss, shear force, or meat color (lightness)	3 h lairage after transport restored plasma corticosterone level; 3 h transport induced glycopenia	Poultry	Unstressed control compared with 45 min transport, 45 min lairage compared with 45 min transport, 3 h lairage compared with 3 h transport, 45 min lairage compared with 3 h transport, 3 h lairage
	Sheep subjected to 18 h lairage had the lowest preslaughter live weight but the highest cold carcass dressing percentage; Sheep subjected to 30 min lairage after transport showed lower cooking loss and higher pH_0, $pH_{24\,h}$, and shear force value	Transport increased plasma cortisol, CK, LDH, and glucose levels; 18 h lairage decreased CK, LDH, and glucose levels	Sheep	75 min transport, 18 h lairage compared with 75 min transport, 30 min lairage compared with no transport, 30 min lairage
Stunning	Head to brisket stunning increased postmortem muscle pH decline and induced paler meat with higher drip loss; head only tongs and CO_2 stunning improved carcass quality	–	Pigs	Gas stunning using 90% CO_2 compared with head only manual electrical stunning compared with head to brisket electrical stunning
	Gas stunning slowed down postmortem pH decline; stunning had significant effects on meat quality traits (meat color, WHC, cooking loss, and drip loss) at 7 d postmortem	–	Sheep	Slaughtered without stunning compared with electrically stunning compared with gas stunning using 90% CO_2

Table 1. Continued...

Factor	Carcass and meat quality traits	Stress responses	Species	Pre slaughter handling conditions
	Stunning affected cooking loss, color coordinates, and texture parameters; the stunned percussive group had better sensory attributes (odor, flavor, tenderness, and overall acceptability) than the non-stunned group	–	Cattle	None-stunning and slaughtered under Turkish slaughter procedure compared with electrically stunning compared with percussive captive bolt stunning
	5 V caused wing damage, 45 V caused pectoralis major and pectoralis minor damage; 5 V decreased muscle $pH_{2\,h}$ postmortem; 5 and 45 V increased drip loss and decreased shear force value	5 V stunning caused the highest plasma corticosterone and lactate levels	Poultry	Electrical stunning with 5, 15, 25, 35, and 45 V at 750 Hz for 10 s
	Electrical stunning impaired breast meat color by decreasing a^* at 1, 3, and 9 d. 150 V, 60 Hz stunning reduced lipid oxidation in breast meat	65 V, 1000 Hz stunning decreased plasma triiodothyronine/thyroxine, while increased corticosterone and uric acid levels	Poultry	Slaughtered without stunning compared with electrical stunning with 65 V, 1000 Hz compared with electrical stunning with 150 V, 60 Hz
Other handling procedures				
Catching/loading	Loading method had no effects on live weight and slaughter data of rabbits; Rough loading increased cooking loss while had no effects on other meat quality traits	Loading method had no effects on hematological and biochemical stress parameters	Rabbit	Smooth (carefully place each rabbit into the transport crates) compared with rough (hurriedly and carelessly throw each rabbit into the crates)
	The catching method did not influence the percentage of bruises or meat quality	Mechanical catching increased dead-on-arrival rate and plasma glucose level	Poultry	Mechanical catching (catching machine containing rotating, hydraulically driven cylinders) compared with manual catching (professional catching teams)
Improper/poor handling	Rough handling increased meat temperature $T_{60\ min}$ and decreased $pH_{60\ min}$ postmortem while had no significant effect on other meat quality traits	Rough handling increased plasma lactate level	Pigs	Gentle (no use of stick or electric prod, pig not slipping, falling, nor emitting high-pitched vocalizations) compared with rough (where any of these occurred)
	The use of electric prodders reduced WHC, including increased drip loss, purge loss, and cooking loss independent of muscle pH and temperature; cattle undergoing electric prodders induced tougher meat with inferior quality rated by the consumer panel	The use of electric prodders increased plasma lactate level	Cattle	Control group (no electric goads used preslaughter) compared with stress group (6 prods given with an electric goad over 5 to 10 min)
Crating	Crating density had no significant effects on meat quality or lipid peroxidation levels	High crating density induced higher Δ rectal temperature, plasma corticosterone, and heat shock protein 70 mRNA levels	Poultry	High (0.0350 m^2/broiler) compared with low (0.0575 m^2/broiler) crating density
Shackling	Shackling decreased pH 15 min postmortem and increased a^* of breast meat while had no significant effects on meat quality traits of thigh meat	Shackling increased glucose, cholesterol, and heterophil to lymphocyte ratio. 120 s shackling induced the highest level of corticosterone and CK	Poultry	Control group (10 s) compared with 30 s compared with 60 s compared with 120 s shackling

Ventilation device (Figure 1) contains an air inlet duct 1 equipped with a fan 2 and an electric motor 3 and a water sprayer 4, an air funnel 5 with a control valve 6 and supply air ducts 7,8 with control valves 9 air outlets 10 to a ventilated room 11 with temperature closers 12, connected by means of a pneumatic lock 13 with an air inlet duct 1 and placed in the soil below the freezing mark of the latter and a program climate controller 14 with temperature sensors 16, 17, 19,20 and speed 15, humidity 18, connected to the electric motor 3 of the fan 2 by the control valve 6, 9 of the air funnel and supply air ducts 7, 8 and the spray 4 and closers 12 of the temperature.

The device contains two supply air ducts 7, 8 to ensure the continuity of the supply of heated air to room 11 while charging one of them.

Assembly and manufacturing of the ventilation device are carried out from prefabricated modular elements selected in accordance with the volume of required ventilation air and the type of agricultural premises.

In the cold period of the year, heavy fresh air flows into the air inlet duct 1 and enters the open-air duct 7 through the airlock 13, contacts the surface of its walls, is heated by the soil heat

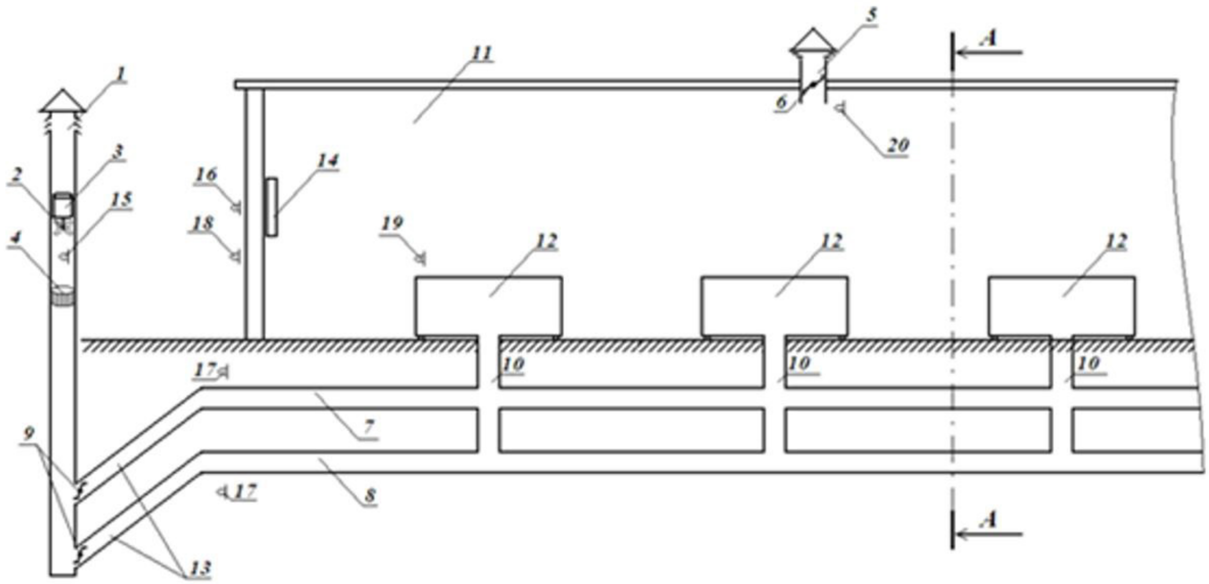

Figure 1. Functional scheme of the ventilation system.

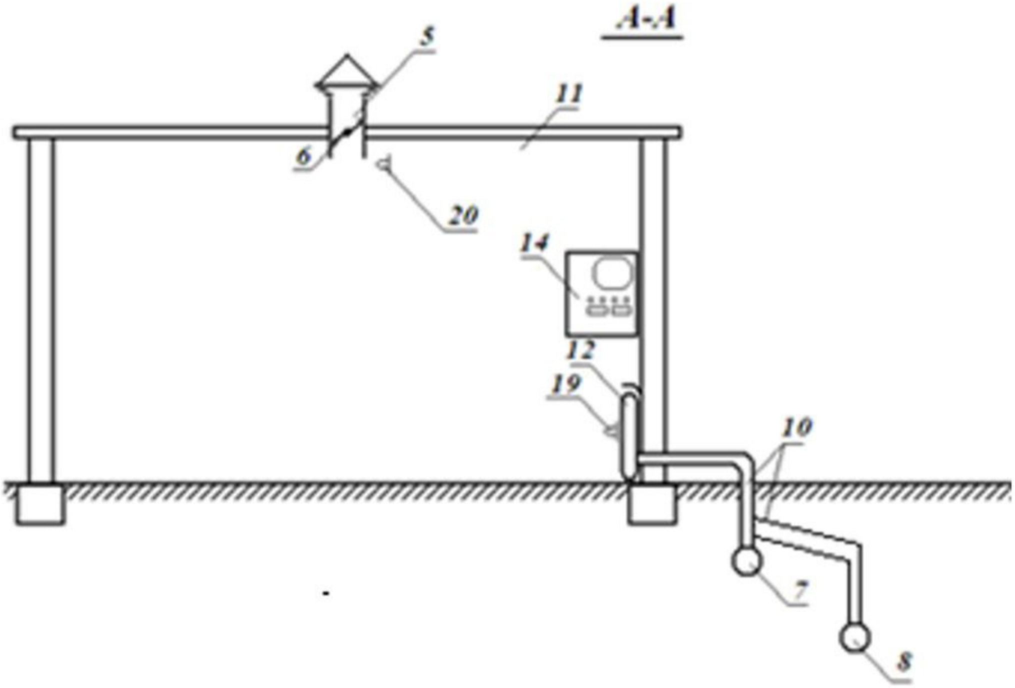

Figure 2. The section on A-A of Figure 1.

and moves up, exits through the outlets 10c room 11, flowing around the temperature closer 12.

Airlock 13, the threshold of which is located below the bottom of the air ducts 7, 8 does not allow the exit of heated light air from the air duct to the air inlet duct 1. This ensures strictly one-way gravity movement of fresh air.

The exhaust air is withdrawn from the ventilated room through the air funnel 5 with a control valve 6 controlled by the microclimate program controller 14.

The program controller 14 controls the operation of the electric motor 3 of the fan 2, which supports the set speed of the gravity flow and the control valves 9, supply air ducts 7, 8,

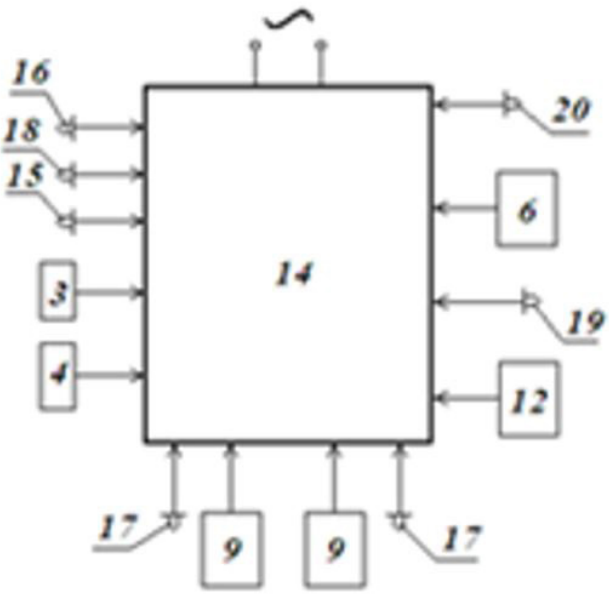

Figure 3. Block scheme of control of the electric motor and control valves of the supply air ducts and air funnel, sprayer, and closers.

providing a set threshold for the temperature of the gravity flow, as well as the temperature closer.

As the temperature of the walls of the air duct 7 or the soil mass decreases, the intensity of heat removal decreases, and at a certain temperature value, the set threshold exceeds the normalized value. At this moment, at the signal of the soil temperature sensor 17, the microclimate controller 14 closes the supply air duct control valve 7 and opens the air duct valve 8. The soil mass around air duct 7 recovers its natural temperature after a while, i.e., it is recharged, and the soil mass around air duct 8 is cooled, i.e., it is discharged. When the soil temperature reaches the normalized value by means of sensor 17, the microclimate controller 14 closes valve 9 of the supply air duct 8 and opens valve 9 of the air duct 7. Thus, the supply air ducts alternately operate in charging and discharging mode and provide a normalized stable supply air temperature, i.e., stabilization.

The heated supply air supplied to the room flows around the temperature closer to 12, its temperature rises to the normalized value. Enabling and disabling closers is carried out by the microclimate controller 14 via the temperature sensor 19. Closers 12 provide radiant and convective heat exchange in the process of creating a local microclimate.

Valve 6 of the air funnel 5 regulates the outlet of exhaust air, and its operation is controlled by the microclimate regulator 14 by means of a temperature sensor 20.

As the external temperature increases, the speed of the gravity flow decreases, and at a certain temperature value, the flow rate will be insufficient to provide normalized air exchange. At this moment, at the signal of the outdoor temperature sensor 16 and the flow rate sensor 15, the microclimate controller 14 connects the electric motor 3 of the fan 2.

In the warm period of the year, the heated fresh air is pumped by a fan 2 through the air inlet duct 1 into the air duct 7, from where the air enters the ventilated room through outlets 10. When passing through air duct 7, the heated fresh air is cooled by transferring heat to the soil through its walls. Air ducts 7, 8 will also work in discharge and charging mode during the cold period of the year. Depending on the required humidity parameters of the ventilated fresh air, it is moistened with water through a spray 4.

Sprayer 4 is controlled via the microclimate controller 14 by means of the outdoor humidity sensor 18 and provides the required humidity of the supplied air.

According to this scheme, an experimental energy-saving ventilation system for a sheepfold was designed and built, and production tests were conducted during the lambing period.

2 Methods of research

When designing an energy-saving ventilation system, the differential equation of the soil temperature field around the air duct of the ventilation system is considered (Abreu et al., 2021):

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial R^2} + \frac{1}{R}\frac{\partial t}{\partial R}\right) \tag{1}$$

where a is the thermal conductivity of the soil.

Boundary conditions of Equation 1 are determined by Equation 2:

$$t = t_s at 1. \tau = 0; 2. R \to \infty, \tau \geq 0$$
$$3. -\lambda \frac{\partial t}{\partial R} = \alpha\left[t\left(R_o, \tau\right) - t_s\left(\tau\right)\right] = 0 \tag{2}$$

where λ is the thermal conductivity of the soil;

α - coefficient of heat transfer of the channel walls.

Average integral air temperature along the length of the channel with the total heat exchange area F is determined by Equation 3 (Carnovale & Phillips, 2020):

$$t_{av}\left(\tau\right) = \frac{1}{F}\int_0^F t\left(x, \tau\right) dF \tag{3}$$

where $t\left(x, \tau\right)$ is the local temperature, determined from the heat balance equation of the air duct area dF (Equation 4):

$$cGdt = \alpha\left[t\left(R_o, \tau\right) - t\left(x, \tau\right)\right] dF \tag{4}$$

The solution of Equation 2 has the form given by Equation 5 (Ayantunde et al., 2021):

$$\phi_x = \frac{t(x,\tau) - t(R_o,\tau)}{t_0 - t(R_o,\tau)} = \exp\left(\frac{-\alpha F_x}{cG}\right) \quad (5)$$

where $t(R_o,\tau)$ - the average length of the channel wall temperature at the time under consideration; F_x - the heat exchange area of the channel to the cross-section x.

The solution of the differential equation allowed us to calculate the parameters of the energy-saving ventilation system. A special information and measurement system was developed to record the thermal parameters of the ventilation system, i.e., the temperature of the outdoor, indoor air, soil, and relative humidity of the outdoor and indoor air.

3 Results and discussion

The farming industry's transportation is a significant operation. It typically causes stress to the animal and might result in the exhaustion of muscle glycogen stores before slaughter, which raises the meat's final pH and causes darker meat with a lower expressed juice value (Randall, 1993; Weeks, 2008). temperature and pH have an impact on meat softness, which is one of the most significant quality attributes. Consumers often use color as a quality indication since it is an essential physical feature of meat. Consumers are becoming more conscious of the ethical issues surrounding meat production, and they prefer meat from animals that have been treated humanely (Jendrisakova et al., 2011). An experimental energy-saving ventilation system was built in a sheepfold for lambing in the Almaty region. The plan and photograph of the sheepfold are shown in Figures 4 and 5.

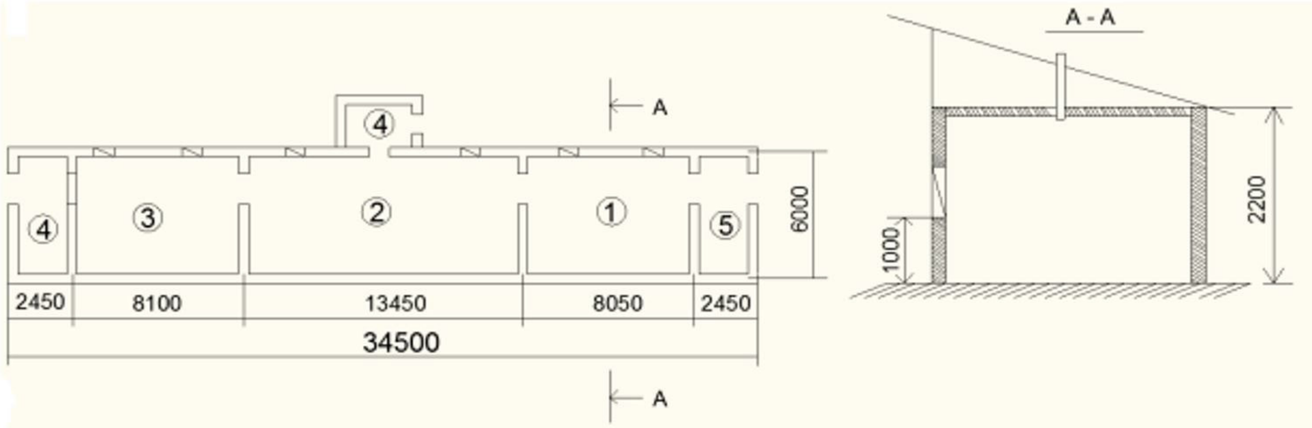

Figure 4. Plan of the sheepfold for lambing; ; 1 - maternity barn; 2 - room for keeping sheep; 3 – room for keeping lambs from 2 months; 4 - tambours; 5 - electric board.

Figure 5. Sheepfold for lambing.

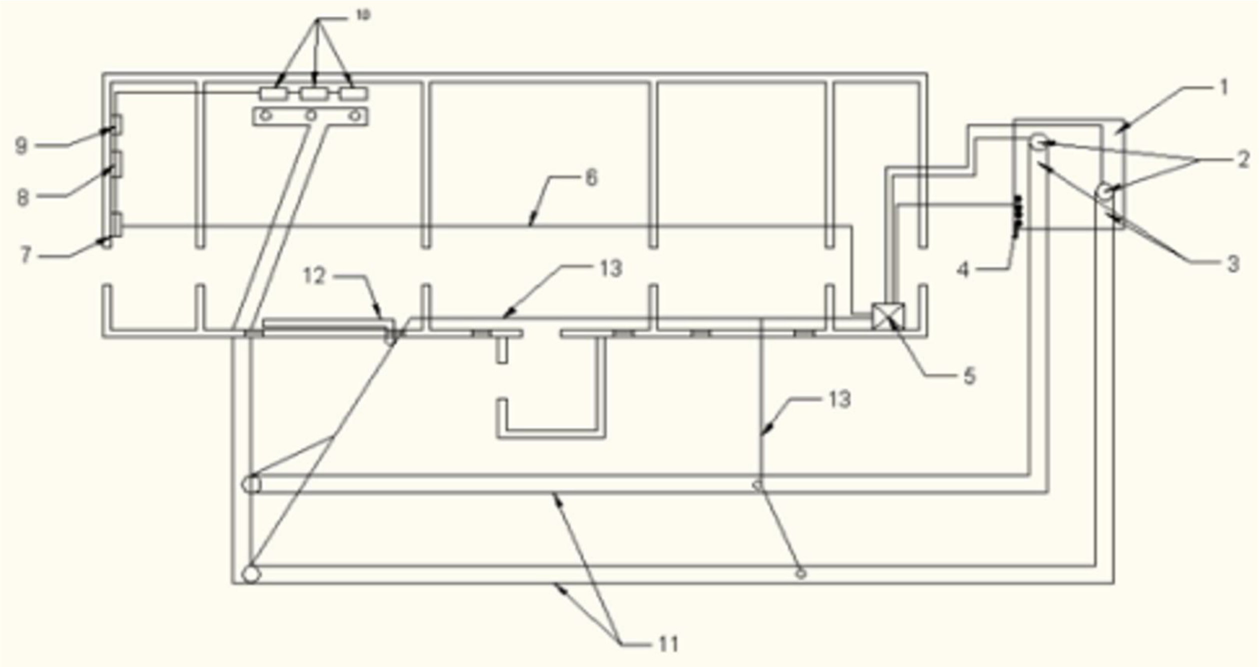

Figure 6. Flow chart of an experimental energy-saving ventilation system for a sheepfold; 1 - room of the air inlet duct; 2 - supply vertical air ducts; 3 - supply horizontal air ducts; 4 - ground temperature sensors; 5 - control cabinet; 6 - power wiring; 7 - power board; 8 - electric meters; 9 - reducing transformer 220/22 V; 10 - closers - electric heating panels; 11 - underground heat exchangers-horizontal air ducts; 12 - air funnel with air duct; 13 - sensor wiring.

The scheme of an experimental energy-saving ventilation system for a sheepfold is shown in Figure 6.

Underground heat exchangers - air ducts were made of corrugated plastic pipes produced by "EPA Almaty" LLP. Pipes are made of high-density polyethylene with nominal internal diameters from 110 mm to 630 mm. GOST 18599-2001.

Wall profile of the "corrugation" type. The pipes are manufactured with a spigot and socket connection. They are connected via O-ring. They have a hollow structure in the form of hollow channels of a rectangular cross-section perpendicular to the axis of the pipe section, and the inner layer is straight and smooth.

The specially designed outer surface of the pipes has a high ring stiffness and makes them more resistant to compressive loads (transport, soil water, permafrost, and soil compaction), and the elastic structure of the pipes protects them from destruction when exposed to overloads. As a material, high-density polyethylene has: high tensile strength, high thermal stability, and is not subject to corrosion. Production tests of the energy-saving ventilation system were carried out in two stages: winter and summer.

When testing an energy-saving ventilation system in winter, it was found that the air temperature in the sheepfold premises ranged from + 5.4 °C to +6.0 °C, on average +5.6 °C, with the number of measurements n = 72.

The relative humidity of the sheepfold premises averaged 79.2% (at n = 72). The maximum and minimum relative humidity values were 93.4% and 64.1%, respectively. At the lowest outdoor temperature - 18 °C (04.02.2014), the supply air temperature reached +6 °C. The flow rate of the supplied air varied between 70-140 m^3/h depending on the outdoor air temperature. The maximum heat output of the unit was 2.2 kW.

When testing an energy-saving ventilation system in summer, it was found that the air temperature in the sheepfold premises ranged from + 16.6 °C to +27.29 °C, on average +22.3 °C, with the number of measurements n = 820.

The relative humidity of the sheepfold premises averaged 30.5% (at n = 820). The maximum and minimum relative humidity values were 58.88% and 10.37%, respectively. At the highest outdoor temperature of +33.4 °C, the supply air temperature reached +19.6 °C, and the humidity increased from 12% to 23%. The flow rate of the supplied air was 140 m^3 /h. The cooling capacity of the unit was 2.6 kW.

4 Conclusions

Sheep transported for 3 hours in an open truck at 42 °C may exhibit substantial reactions involving elevated nor-adrenaline, adrenaline, cortisol, and dopamine concentrations (Hall & Bradshaw, 1998; Knowles et al., 1995). The quality of the meat worsened as well. Low-voltage electrical stimulation of sheep carcasses can help mitigate the negative effects of transportation stress on meat quality. In order to provide safe and quality food, one of the most important aspects of farm animal welfare is to maintain animals clinically healthy, free of disease and stress, especially in intensive breeding. This is a critical problem for the global food business since it is directly related to human health and wellbeing. A mathematical model of heat exchange processes in an energy-saving ventilation system has been developed. The ratio of the optimal radius and length of the air duct, the airflow rate of the soil temperature, and the volume of heat in the ventilation system are determined. The technological, functional, and concept schemes of an energy-saving ventilation system have been compiled. The parameters of a ventilation system for a sheepfold using soil heat were determined.

Production tests of an experimental modular energy-saving ventilation system were carried out in two stages: winter and summer. Registration of thermal parameters of the ventilation system was performed remotely using the MasterScada system.

Assessment of the technical and economic efficiency of the work performed shows that energy consumption is reduced by up to 40-50% when implementing an energy-saving ventilation system, depending on the type of agricultural premises.

During the testing periods, the energy-saving ventilation system provided the energy-saving mode and the required zootechnical parameters of the microclimate in the maternity barn of the sheepfold. The energy-saving ventilation system was adopted for economic use and recommended for implementation in sheep farms.

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