Обґрунтовано і побудовано наближену фізичну модель формування температурного режиму у цеху поросят і свиноматки із врахуванням впливу окремих елементів системи комбінованого опалення. Визначено закономірності впливу теплових і технічних характеристик окремих елементів даної системи на температурний режим зон перебування поросят і свиноматки та отримано залежності для визначення температури повітря у цих зонах

Ключові слова: комбінована система опалення, інфрачервоний нагрівач, опалювальна панель, нагрівальний килимок

Обоснована и построена приближенная физическая модель формирования температурного режима в цехе поросят и свиноматки с учетом влияния отдельных элементов системы комбинированного отопления. Определены закономерности влияния тепловых и технических характеристик отдельных элементов данной системы на температурный режим зон пребывания поросят и свиноматки и получены зависимости для определения температуры воздуха в этих зонах

Ключевые слова: комбинированная система отопления, инфракрасный нагреватель, отопительная панель, нагревательный коврик

STUDY OF THE THERMAL MODE OF A BARN FOR PIGLETS AND A SOW, CREATED BY COMBINED HEATING SYSTEM

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1. Introduction

The standards of living of the population are closely linked to development of agriculture, including livestock production, in which swine breeding is one of the most important areas. A significant part of production technology of swine breeding, influencing further progress of the industry, is introduction of intensive technologies that use full-ration feeding, high-tech equipment for pigs keeping and feeding, heating, ventilation, etc. [1].

Technology of pigs breeding is based on the principles of workshop keeping such as in barns of piglets and sows [2]. There are a number of problems that are associated with high quality pigs keeping, particularly a decrease in preservation of young pigs, an increase in piglets' mortality within first days and hours of life, increased risk of disease.

In comparison with other farm animals, piglets are born least mature, their live weight does not exceed 1 % of weight of an adult pig. Most pigs lose around 5–6 % of their original weight after birth within 2–3 days (sometimes 4–7 days) because within first 10 days, the amount of water in their bodies decreases by 6–7 %. The most important periods of piglets breeding are the following: first 2–3 days after birth when the body of a piglet adapts to new conditions of existence; the fifth-seventh day when due to lack of iron in the milk of a sow, a piglet begins to develop anemia; days 14–2,

when immunity against different diseases, acquired with colostrum of a sow, is lost; days 35–60 coincide with the time of piglets weaning and, therefore, deprivation of their mother's milk and full transition to other feed [3].

Piglets are born without hair cover, that is why they are very sensitive to cold. If in the area of animals' keeping the air temperature is lower than 15 ºC, piglets under such conditions get too cold, often get sick and may die. But it is much more difficult for an adult pig to tolerate high temperature than low temperature. A temperature increase influences negatively the vital activity of the pig's organism and we can observe thermal overload. These data indicate that in pigs and sow barns, it is necessary to create a separate microclimate, which corresponds to physiological needs of various categories of animals. However, the important task is to create local heating of animal keeping zones. It offers an opportunity to concentrate heat in zones of pigs and sow keeping, and thus not to heat the whole volume of premises.

One of the ways of solving the problem of heating supply to barns of piglets and sows is introduction of energy-efficient heating systems, which make it possible to maintain a desired temperature mode in animal keeping places. In addition, it is important to analyze effectiveness of proposed technical solutions and determine technical and economic indicators.

A relevant problem is still to create new energy efficient heating systems, which take into account specific features

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of modern technological process in pigs and sow barns, temperature modes, as well as physiology of animals.

2. Literature review and problem statement

The most common systems of maintaining temperature modes in piglets and sow barns are systems of air and under-floor heating, and infrared heating. One of the variants of provision of necessary temperature conditions in the zone of piglets keeping is a heating device that consists of the case that can move around to the farrowing place (Fig. 1). In the case, there is a fan for air supply directly to the zone of piglets keeping, a grate, which prevents extraneous stuff from getting in the fan, the exhaust hole, which is made in the form of the diffuser. An important element of such a device is a motion detector, which gives the signal to the fan to turn on when a sow takes a vertical position, respectively, in the supine position the fan will be turned off [4].
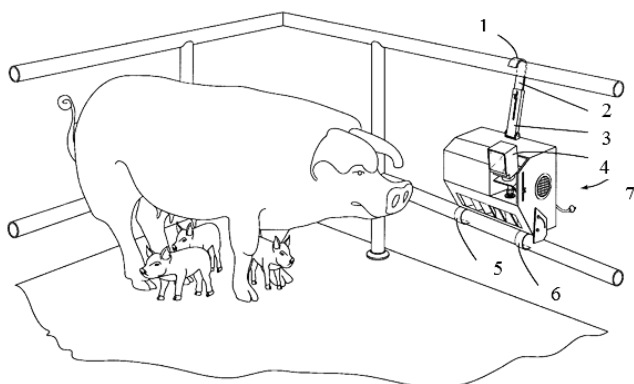

Fig. 1. Device for heating the piglets: 1 — c-shaped mounting element; 2 — telescopic element; 3 — fixing node; 4 — motion sensor; 5 — second fixing element; 6 — c-shaped bottom mounting element; 7 — heating device

This device enables maintaining a certain thermal mode in the zone of animal keeping, however, the design of the machine makes it impossible to keep .young piglets and a sow separately. There is a danger of injuring piglets by a sow, since they are near it.

For local heating of the zone of piglets keeping, infrared lamps and infrared heaters are installed. Heaters are installed directly into piglets' resting place [5]. During irradiation, blood intensively flows to the peripheral vessels, which creates a thermal barrier that prevents the organism from overcooling. In optimum doses, infrared rays have anti-cold properties [6, 7]. The height of infrared lamps mounting depends on air temperature in the room, as well as on the animal's body temperature. The assigned temperatures were measured using an infrared sensor [8]. It was proposed to keep piglets in a special box, which is equipped with an infrared heater. It was suggested to control temperature of surfaces in the box with the help of sensors. As piglets grow, air temperature must gradually decrease [9]. However, lamps do not provide a required temperature mode in the zone of sow keeping.

In order to provide a comfortable condition in premises with the piglets, as well as to save power resources, there was proposed a hybrid heating system that includes solar collectors, placed on the roof and an external wall of the building, a heat accumulator, a heat absorber, as well as the floor, which is made in the form of a grate for better heat distribution. Experimental research in thermotechnical characteristics of this system lasted for 8 months. It was found that the use of this system can decrease energy consumption by 25–30 % compared to traditional heating systems. However, there are a number of significant shortcomings, including lack of flexible regulation of a temperature mode in the room, as well as creation of a separate temperature mode in the barn for piglets and a sow [10].

The problem of using solar energy for heating premises of piglets keeping was also studied by H. Mun, S. Ahmed and others. The scientists studied a decrease in CO_2 level and saving of power resources when using solar batteries. It was found that the level of CO_2 emissions decreased by 15 %, and use of electricity – by 260 kWh in comparison with the traditional system [11]. A shortcoming of this system is also difficulty in temperature regulation in the room and absence of possibility of zoning.

Based on conducted analysis of the known findings of theoretical and experimental research, it is possible to emphasize the need for development of innovative heating systems that make it possible to provide a separate microclimate in the zones of animal keeping. In this case, there is a need for special systematic studies on establishing heat transfer patterns in a barn of piglets and a sow. Considerable interest is consideration of possibility of implementation of combined heating systems.

An energy efficient system of combined heating is proposed, based on existing ideas about specificity of the technological process and taking into account physiological characteristics of piglets and sows, as well as physical essence of heat supply to zones of animal keeping [12].

3. The aim and objectives of the study

The aim of present research is to scientifically substantiate and develop an energy efficient system of combined heating with local heating elements, which is based on in-depth analysis of the temperature mode in barns of pigs and a sow and on this basis to elaborate guidelines for its rational use.

To accomplish the set goal, the following tasks had to be solved:

– to substantiate the physical model of the barn of piglets and a sow and expediency of application of local heating of animal keeping zones;

– to perform theoretical and experimental research in features of formation of a separate temperature mode in barn of piglets and a sow;

– to develop a heating device for barn of piglets and a sow for heating supply of animal keeping zones;

– to propose an energy efficient system of combined heat supply for the barn of pigs and a sow using local heating elements.

4. Materials and methods of study of thermal mode in the barn for piglets and a sow

4. 1. Analytical studies of thermal mode in the barn for piglets and a sow

Peculiarity of the technological process in barns of pigs and a sow lies in the fact that a sow stays in the barn within three months. Throughout one month before farrowing, air temperature in the place of animal keeping should be main-

tained at the level of 15–17 °C, and throughout two months with piglets, air temperature must be within 18–20 °C [1]. To provide a required temperature mode, an electric heating panel is installed, the surface heating degree of which is changed with a thermal regulator.

In the place of piglets keeping, air temperature is much higher, and as they grow, varies from 30 to 22 °C. Thermal condition is formed by an electric heating mat in the resting place of piglets and by an infrared heater over the feeder, the installment of which causes signs of positive biological changes in animals. A change in thermal capacity of heating devices gives an opportunity to provide a required temperature mode of this zone.

Air humidity, as well as concentration of harmful gases in the barn of piglets and a sow, is assimilated with the help of sufficient air exchange. The air is supplied to the zone of piglets and a sow keeping through a perforated duct and removed through the channel.

Taking technology of piglets and a sow keeping as a basis, and considering peculiarities of functioning of the combined heating system, the main concepts and prerequisites for substantiation of a physical model were formulated. In this case, phenomena that are associated with formation of the temperature mode of a barn were taking into account.

The developed physical model made it possible to construct the scheme of heat flows, which fully reflects heat exchange processes in places of animal keeping.

Modeling of heat flows was based on graph theory [13]. This approach enables us to effectively solve complex problems of thermotechnical physical processes of a barn of piglets and a sow.
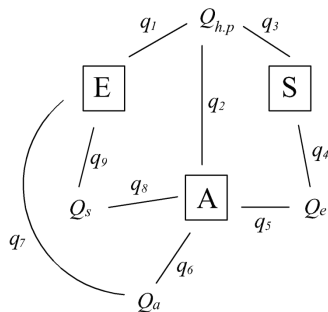

Fig. 2. Graph of heat flows over the zone of sow keeping

In the studied area, the following thermal air absorbers were separated: air – (A); protective fences (E); a sow (S). In addition, the following heat sources were selected: a heating panel ($Q_{h.p}$); a sow (Q_s); air (Q_a); protecting fences (Q_e), which are the graph's vertices. Heat flows of the zone of sow keeping, which correspond to heat exchange between the i-th heat sources and thermal absorbers, are shown on the graph in the form of edges that connect the vertices (Fig. 1).

Air temperature in the sow keeping zone was determined. We generalized empirical and theoretical data relating to formation of thermal state for conditions under consideration and obtained functional dependence (1):

$$t_{s.a}^s = f\left(A_{h.p}, F_s, \alpha_k, \alpha_{pr}, t_s, t_{out}, t_r, t_f\right). \qquad (1)$$

Based on the developed physical model, the scheme of thermal flows for the situation in the zone of piglets keeping

was constructed, which, in turn, helped to plot a generalized graph of heat flows. As for thermal absorbers, they included, firstly, air (A), secondly, protective fencing (E), and thirdly, piglets (P). The edges of the graph represent thermal interaction of absorbers with heat sources, which included a heating mat ($Q_{h.pd}$); piglets (Q_{pig}); an infrared heater ($Q_{i.h}$); air (Q_a); protective fences (Q_e). According to this, extended matrix of separated thermal absorbers and the system of balance equations for each of them was formulated. It enabled us to establish functional dependence of air temperature in the zone of piglets keeping (2):

$$t_{s.a}^{pig} = f\left(A_{h.pd}, F_{pig}, A_{i.z}, T_1, \alpha_k, \alpha_{pr}, t_{pig}, t_{out}, t_r, t_f\right), \qquad (2)$$

where $A_{h.pd}$ is the area of the heating mat, m²; F_{pig} is the piglet's area, m²; $A_{i.z}$ is the area of irradiation zone, m²; T_1 is the temperature of surface of the infrared heater, K; t_{pig} is the temperature of a piglet's body, °C.

MATLAB applications were used on order to obtain relationship between main parameters affecting the thermal state of the zone of piglets – the temperature of the heating mat $\tau_{h.pd}$, °C, outdoor air temperature, t_{out}, °C, air temperature in the zone of piglets keeping $t_{s.a}^{pig}$, (Fig. 3).
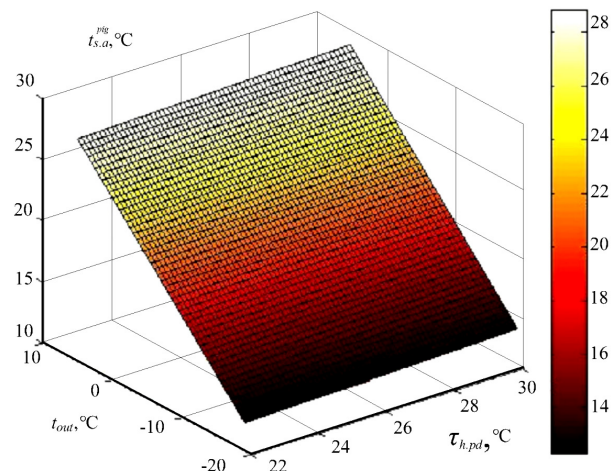

Fig. 3. Distribution of air temperature in zone of pigs keeping depending on temperature of heating mat and outdoor air temperature

In order to simplify analysis of thermophysical processes, some assumptions were made. Thus, temperature range of the surface of the heating mat was from 22 to 30 °C, outdoor air temperature changed from 10 to 20 °C. Two factors were accepted as variable – outdoor air temperature and surface temperature of the heating mat. To plot graphical dependences, the rest of the parameters that directly affect the thermal condition of the zone of piglets keeping, were accepted as non-variable.

4. 2. Experimental research into temperature mode of the barn for piglets and sow

Experimental studies were conducted to determine the influence of the heating panel, the heating mat, as well as the infrared heater on parameters of temperature in zones of piglets and sow keeping.

Procedure of experimental research was presented, experiment planning, mathematical processing and analysis of obtained data were performed.

It is necessary to separate a number of consecutive experimental studies in the complex of conducted experimental research:

– first, the study of a temperature mode in the zone of sow keeping, which was formed by the heating panel;

– second, experiments to determine a temperature mode in places of piglets keeping that was provided by the heating mat;

– third, determining of the influence of the infrared heater operation on the thermal condition at the place of piglets keeping.

When it comes to research at the first stage, it should be noted that the experiments were carried out on the setup, shown in Fig. 4.
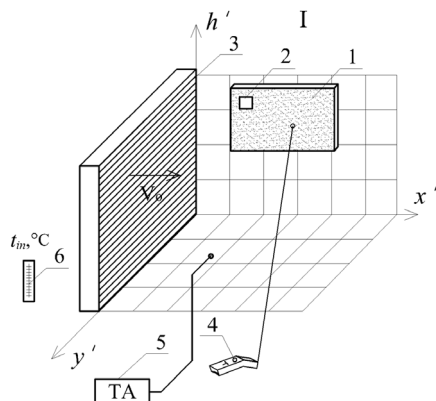

Fig. 4. Schematic of experimental setup for achieving the temperature mode in a sow keeping zone: 1 — heating panel; 2 — thermostat; 3 — air distributor; 4 — pyrometer "Nìmbus-530"; 5 — thermoanemometer ATT-1004; 6 — thermometer TM6

Temperature mode was formed by heating panel 1, a degree of surface heating of which changed with the help of thermostat 2 from 60 to 73 °C and was determined by pyrometer 4. Air flow was created by air distributor 3, air temperature and velocity were measured with thermoanemometer 5.

Studies were conducted based of experiment planning, the input factors of which included: relative width of operation area $x_1 = \bar{y}' = y' / y'_{max}$; y' is the width of the sow keeping zone, m; y'_{max} is the maximum width of this zone, m; air velocity $x_2 = V_o$, m/s; temperature of the heating panel $x_3 = \tau_{h.p}$, °C. In this case, response function was the relative temperature in the zone of sow keeping, which was determined: $\bar{t}^s = t_{in} / t^s_{s.a}$; t_{in} is background air temperature, °C; $t^s_{s.a}$ is the air temperature of the zone of sow keeping, °C. Region of determining of input parameters was within limits of: $\bar{y}' = [0...1]$; $V_o = [0,1...0,5]$ m/s; $\tau_{h.p} = [60...73]$ °C.

According to results of regression analysis, approximating polynomial (3) took the form:

$$y = 0,909x_0 + 0,011x_1 + 0,056x_2 - 0,016x_3. \qquad (3)$$

Based on analysis of regression equation coefficients, it was concluded that response function was most essentially influenced by factor x_2 – air velocity V_o, m/s; and factors x_1– relative width of the zone of sow keeping and x_3 – temperature of the heating panel, $\tau_{h.p}$, °C, influence to less extent.

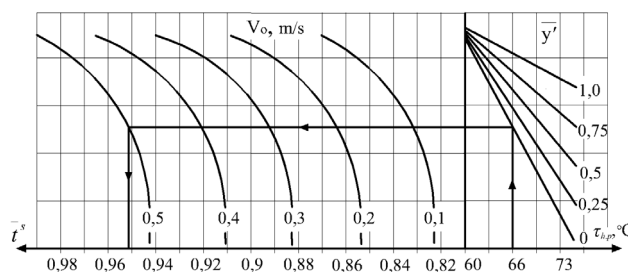Results of the experiment are shown in Fig. 5.

Fig. 5. Graphic dependence of relative air temperature $\bar{t}^s$ on the relative width of barn for piglets and sow $\bar{y}'$, air velocity V_o, m/s, and temperature of heating panel, $\tau_{h.p}$, °C

It was found that a decrease in air temperature in the zone of sow keeping at getting more distant from the panel is virtually the same for different velocity values and is approximately 2.5 °C.

Studies at the second stage were aimed at determining of air temperature distribution in resting zone of piglets. It was formed by the heating mat, the surface heating degree of which changed from 30 to 22 °C, and which was studied on the experimental setup, shown in Fig. 6.
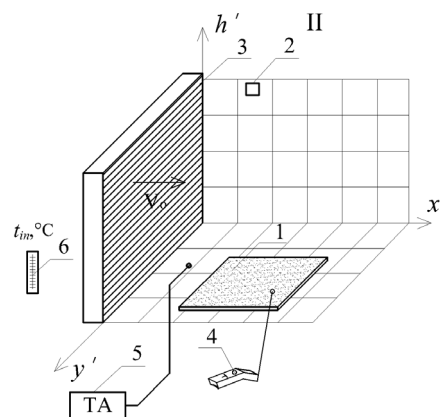

Fig. 6. Schematic of experimental setup for study of temperature mode in zone of piglets keeping: 1 — heating mat; 2 — thermostat; 3 — air distributor; 4 — pyrometer "Nìmbus-530"; 5 — thermoanemometer ATT-1004; 6 — thermometer TM6

Experiment planning was conducted. The following factors were taken into account: $x_1 = \bar{h}' = h' / h'_{max}$ is the relative height of operation zone; h' is the height of the zone of piglets keeping, m; h'_{max} is the maximum height of this zone, m; $x_2 = V_o$ is the air velocity, m/s; $x_3 = \tau_{h.pd}$ is the temperature of the heating mat, °C. Relative air temperature in the zone of piglets keeping $\bar{t}^{pig} = t_{in} / t^{pig}_{s.a}$; was accepted as response function y; t_{in} is the background air temperature, °C; $t^{pig}_{s.a}$ is the air temperature of the piglets' keeping zone, °C.

As a result of experimental research at the second stage, we acquired graphic dependence for determining of air temperature in piglets' rest zone at different air velocities and constant average temperature of the heating mat (Fig. 7).

Having analyzed the resulting dependence, it is possible to conclude that air temperature in this zone slightly varies in height. Maximum deviation at the zone boundary is 1.3 °C.

Resulting empirical dependence for determining of relative indoor air temperature in the piglets keeping zone with the use of the heating mat:

$$\overline{t^{pig}} = (0,9 + 0,073 \cdot V_o) +$$
$$+ (-0,00035 - 0,0051 \cdot V_o) \cdot ((14,8 - 6 \cdot \overline{h'}) +$$
$$+ (0,3 \cdot \overline{h'} - 0,5) \cdot \tau_{h.pd}) +$$
$$(0,0009 + 0,0038 \cdot V_o) \cdot ((14,8 - 6 \cdot \overline{h'}) +$$
$$+ (0,3 \cdot \overline{h'} - 0,5) \cdot \tau_{h.pd})^2. \tag{4}$$

During experiments at the third of the considered stages, which were performed on the experimental setup (Fig. 8), we studied the temperature mode in the piglets' feeding zone, provided by the infrared heater.
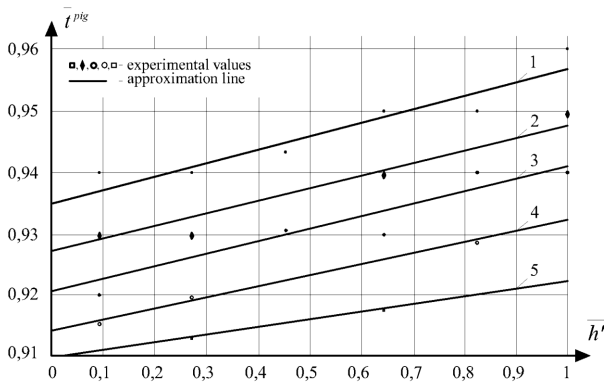

Fig. 7. Dependence of relative air temperature $\overline{t^{pig}}$ on relative height of operation zone $\overline{h'}$ at $\tau_{h.pd}$=26 ºC; y'=0.4 m; x'=0.8 m and at air velocity V_o: 1 — V_o=0.5 m/s; 2 — V_o=0.4 m/s; 3 — V_o=0.3 m/s; 4 — V_o=0.2 m/s; 5 — V_o=0.1 m/s
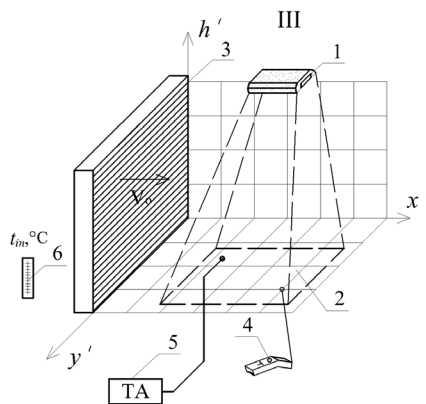

Fig. 8. Schematic of experimental setup for the study of temperature mode in zone of piglets' location: 1 — infrared heater; 2 — irradiation zone; 3 — air distributor; 4 — pyrometer "Nimbus-530"; 5 — thermoanemometer ATT-1004; 6 — thermometer TM6

Planning of the full factorial experiment was carried out, research procedure was described, and obtained results were mathematically processed and presented in the form of graphs, nomograms and empirical dependences. The studies were aimed at determining of air temperature in the piglets' feeding zone, taking into account thermal capacity of the infrared heater, the height of its mounting and air velocity.

Relative air temperature in the studied zone was presented by empiric dependence (5):

$$\overline{t^{pig}} = \left(0,6 - 0,18 \cdot h'\right) + 0,1 \cdot (((1,8 - 1,78 \cdot h_h') +$$
$$+ (0,98 + 0,004 \cdot h_h') \cdot ((1,7 + 5,7 \cdot V_0) +$$
$$+ (-0,0001 - 0,0005 \cdot V_0) Q_{i.n}))), \tag{5}$$

where V_0 is the air velocity, m/s; $Q_{i.n}$ is the capacity of the infrared heater, W; h_h' is the height of mounting of the heater, m; h' is the height of measuring, m.

It was found that with an increase in air velocity and in the height of mounting of the heater, air temperature in this zone decreases.

To prove adequacy of results of laboratory studies, we conducted the studies under real conditions to determine the temperature mode in animal keeping zones, taking into account complex influence of components of the combined heating system. We also performed techno-economic comparison of the proposed combined heating system with the air heating system combined with infrared heaters [14].

Engineering guidelines for calculating the main thermal characteristics of pig farms with pigs and sow barns were developed. The proposed procedure of calculation makes it possible to determine air temperature in the animal keeping zone. To maintain a desired temperature, we calculated the required thermal capacity of each of the constituent elements of a combined heating system, in particular the heating panel in the zone of sow keeping, as well as the heating mat and the infrared heater for heat provision of piglets.

Conducted studies offered an opportunity to obtain dependence for determining of incoming air temperature with consideration of such factors as the number of animals in the pigsty and background air temperature (Fig. 9).
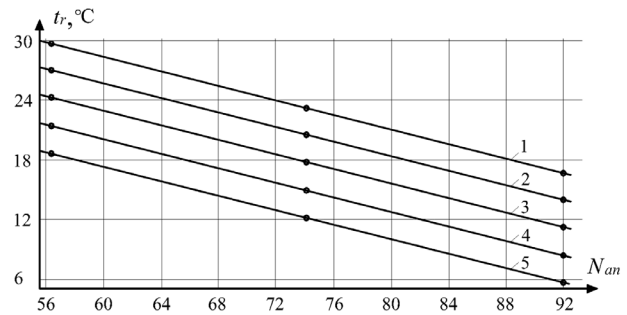

Fig. 9. Dependence of incoming air temperature t_r, ºC on the number of animals N_{an}, at corresponding background temperature t_{in}, ºC: 1 — t_{in}=18 ºC; 2 — t_{in}=16 ºC; 3 — t_{in}=14 ºC; 4 — t_{in}=12 ºC; 5 — t_{in}=10 ºC

These data indicate that at constant background air temperature, it is necessary to increase incoming air temperature with a decrease in the number of animals in the pigsty.

5. Discussion of results of research into temperature mode of the barn for piglets and a sow

Based on the results, obtained during analytical and experimental research in the temperature mode in premises for keeping pigs and a sow, as well as data regarding physiological needs of these animals, the energy effective heating system was proposed. This system consists of the infrared

heater, placed above the feeder, the heating mat, located in the rest area of piglets, as well as the wall heating panel, located in the sow keeping zone. One of the advantages of the proposed system is the possibility to increase the local heating area and to provide creation of the necessary temperature mode for different categories of animals. It gives the opportunity to save energy resources, which would be consumed for heating the whole volume of premises.

We also obtained dependences for determining of air temperature in the animal keeping zone that can be used during designing the heating system in the barn of piglets and a sow. The main factors, affecting thermal condition in the barn, are surface temperature and geometrical dimensions of heating appliances, as well as air velocity.

Subsequently, it is planned to conduct a complex of research to provide the temperature mode in the premises of keeping other categories of pigs, because the developed system has been designed for heating the barn of piglets and a sow in particular.

6. Conclusions

1. Based on physical modeling, we proved the expediency of application of the combined heating system, based on background air supply of the pig farm and local heating of places of animal keeping, particularly heating panels for the zone of a sow, the heating mat and the infrared radiator for the piglets' zone.

2. The complex of research was performed, based on which the patterns of formation of thermal conditions of the barn of pigs and a sow by local heat sources were determined: the heating panel with surface temperature of 60...72 ºC, the heating mat with surface heating degree of 30...22 ºC, the infrared heater with capacity of 500–1,500 W. It was shown that the combined heating systems efficiently provide the standard temperature mode in the barn.

3. The heating device for the piglets and sow barn was developed and protected by the patent of Ukraine [12]. It made it possible to increase the area of local heating of places of piglets keeping and to allow maintaining of process of formation of a required temperature mode for different categories of animals. This device has the infrared heater and the heating mat in the area of piglets' keeping, which differs by the fact that the infrared heater is made in the form of a rectangle, the device is additionally equipped with at least one wall heating panel.

4. The energy efficient system of combined heating, which is based on the local heating zones of animals keeping, was proposed and implemented. The patterns of influence of constituent elements of the system of combined heating on air temperature in the area of animal keeping were established and it was found that:

– at an increase in the temperature of the heating panel by 1 ºC and a decrease in the air velocity by 0.1 m/s, temperature in the zone of sow keeping increases by 8 %;

– at an increase in the temperature of the heating mat by 1 ºC and a decrease in the air velocity by 0.1 m/s, temperature in the zone of piglets keeping increases by 2 %;

– at a decrease in the capacity of the infrared heater by 500 W and in the air velocity by 0.1 m/s, temperature in irradiation zone decreases by 3 %.

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