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Local Heating through the Application of a Thermoelectric Heat Pump for Prenursery Pigs

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Abstract: Mathematical formulation of the animal thermal status has been developed, with the account of two convenience conditions and heat balance, for the floor-mounted heating panel for prenursery pigs. The borders of the heat flux variation range for the floor-mounted heating panel have been determined corresponding to the animal-friendly conditions for prenursery pigs of various age groups. The block diagram of the energy-saving floor-mounted heating panel, comprising the thermoelectric assembly operating in the heat pump mode, has been designed. The method has been described and the corresponding calculations have been made for the basic thermal parameters of the floor-mounted local heating installation, for prenursery pigs, with the application of a thermoelectric heat pump. The experimental installation sample of 116 W thermal capacity (for the heat transfer coefficient from 0.9 W·m^{-2}·K^{-1} to 1.0 W·m^{-2}·K^{-1} and floor temperature in the range of 5 °C to 6 °C) has been developed and manufactured for local heating for prenursery pigs managed in gestation crates. Laboratory tests of the experimental sample of the floor-mounted heating panel have demonstrated high energy efficiency of the heating installation under development. The energy-saving effect (approx. 15% compared to the series-produced equipment designed for local heating of young stock) of the developed installation was achieved owing to the partial heat recuperation of the exhaust ventilating air.

Keywords: thermoelectric heat pump; young stock heating; floor-mounted heating panel; microclimate

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1. Introduction

The importance of energy provision for agricultural enterprises has been growing due to the ascendant increase of energy resource pricing compared to that of the agricultural products. The development and implementation of energy-saving technologies and technical aids into the production processes of the agricultural sector are one of the ways to reduce the energy component in agricultural production costs [1,2]. One basic and essential problem of stock breeding is to ensure animal-friendly temperatures in sow houses where, during the cold seasons, two different temperature fields have to be maintained: one for breeding sows, and the other for prenursery pigs [3]. It means that the air temperature level has to be within the range from 18 °C to 20 °C, for breeding sows, while in the area where prenursery pigs are kept it has to be near 30 °C, gradually decreasing within a period of 26 days down to 24 °C, by the date of breaking-in to milk. The air temperature has to be approx. 23 °C and 21 °C by the end of the first month and at the age of two months, respectively [4].

Today, the independent room conditions for breeding sows and for piglets are provided by creating local heating areas with the help of heated floors, IR thermal radiators, brooders, and piglet kennels [5]. The most favorable conditions for breeding prenursery pigs can be ensured by the application of combined heating when the heat is transferred to the animals both from the bottom and from overhead with the help of infrared thermal radiation and heated floors, panels or mats [6–9]. Heating is mainly achieved by the use of either electric resistance heaters or hot water [10–13]. In order to maintain standard microclimate parameters in animal-breeding premises, a complex energy-saving heat-provision system has been designed, comprising an electric thermal storage (ETS) unit and overhead fan [14]. The energy-saving air heating system featuring the functions of the exhaust air thermal energy recuperation, air ozonizing and deep air flow circulation had been developed [15]. The method for calculating thermal parameters and those of air curtains design, for animal-breeding premises, had been described [16]. A heat-provision and cooling installation with the application of geothermal energy [17] and an energy-saving air dehumidifier on the basis of thermoelectric units, for animal-breeding premises, had been reported [18]. However, in the scale of the entire sow house, the microclimate control process is rather energy-consuming, leading to the growth of energy-related costs in agricultural products.

Paper [19] had made experimental studies of various heating systems for newborn prenursery pigs in farrowing quarters. Four groups of pennages, each including four pennages, were equipped with, respectively, a water-heated mat, a thermoplastic plate, a microporous foam mat and gas infrared heater, and a thermally-insulated concrete floor with gas infrared heater. Prenursery pigs having been kept in pennages with heating system having water-heated mats showed higher average weight (7.72 kg) by the 28-th day compared to those that were kept in pennages with other heating systems. The worst weight indicator (7.26 kg) was obtained for prenursery pigs that were kept in pennages with thermally-insulated concrete floor and gas infrared heating system. Two new types of electric heating panels, with coating made of glass-fiber reinforced plastic and heating elements in the form of 80 W electrothermal films and 90 W electrothermal cable, have been developed [20]. Application of those electric heating panels made it possible to raise the percentage of prenursery pigs alive compared to conventional electric heating panels and 250 W infrared lamps. Three heating system options for prenursery pigs at pig farms during farrowing time were discussed, including overhead infrared heating panels (IRP), an electric 'warm' floor system, and a convective system [21]. It was found that the electric 'warm' floor system is the most energy-efficient solution. At the same time, overhead infrared heating panels (IRP) were the optimal choice in terms of heat comfort for animals.

The effectiveness of the following four options of heating system for prenursery pigs was experimentally evaluated: electrically heated mat (EM), water-heated mat (WM), water-heated 'warm' floors (FH), and infrared heating lamps (IRL). Based on the research results, taking into account statistical data on average daily gain (ADG), mortality rate of prenursery pigs, as well as the effect of heating on their behavior, use of electrically heated mats or 'warm' floors with water heating were considered the most effective local heating system within the period of the first five weeks (starting from the third week) [22–27]. A carbon fiber heater has been developed for the local heating of breeding saw with prenursery pigs, providing the required thermal comfort and reducing power consumption compared to conventional heating lamps (HL) [28].

A mathematical model was developed and verified to control the heat flux rate of the electrically-heated mat for prenursery pigs, depending on the environmental conditions, and the age and weight of the piglets [29]. In paper [30] a mathematical model was developed for predicting the thermal balance and body temperature of pigs in various environmental conditions. Among the heat-transfer modes described in that model were convection into the environment, thermal conductivity through the floor, long wavelength radiation exchange between animals and swine house cladding structures, short wavelength solar radiation, evaporation from the animal skin surface, evaporation and air heating in their breathing passages, as well as heating of swallowed food and water. The temperature of the pig's body was considered as the function of time, taking account of the thermal balance and animal weight, as well as the specific heat capacity and temperature of the animal body.

A mechanical model of the stationary heat balance for prenursery pigs was considered and was further developed with the account of the evaluation of thermal interactions among a number of prenursery pigs and heat transfer by thermal conductivity. The equation for the effective environment temperature for prenursery pigs (EET) was also modified, in order to include the 30-days postnatal period of pigs and the heat transfer coefficient by thermal conductivity. Parameters of the model were supported by the empirical data regarding the thermal component of microclimates, and data on the size of prenursery pigs. The results of modelling have shown that, in the entire microclimate, additional local heat sources (thermal mats and thermal lamps) are able to satisfy the heat demands of prenursery pigs. The equation for EET is more applicable to the microclimate of partially enclosed heated pennages (PEHP) than to heat provision with the use of heating mats (HM) and lamps (HL) [31,32].

At commercial agricultural enterprises, various gestation crate options were designed for breeding sow farrowing and their management with newborn prenursery pigs, in which a fixed location for the breeding sow is provided along with a heated area for prenursery pigs (heated floor, panels, or mats). Since relatively cheap and effective space-saving thermoelectric units and thermoelectric assemblies featuring the heat pump function have appeared on the market, it seems to be relevant and expedient to design an energy-saving installation for the local heating of prenursery pigs which, besides ensuring animal-friendly conditions for the young stock, will make it possible to reduce substantially the energy costs associated with heating local areas in sow houses [33].

The aim of this study was to develop a method of calculation for, and to manufacture and test, an experimental sample of an energy-saving floor-mounted heating panel with the application of thermoelectric modules for prenursery pigs kept in pens.

2. Materials and Methods

2.1. Convenience Conditions and Thermal Balance of Animals

The thermal status of animals can be described by convenience conditions [3]. The first convenience condition is determined by the animal's sensation of thermal comfort while being within the rest area, i.e., its organism is in state of thermal equilibrium, giving out a certain quantity of sensible heat Q_{sh} into the environment without overloading its automatic temperature regulation function [34]:

$$Q_{sh\ max} > Q_{sh} > Q_{sh\ min}, \tag{1}$$

where $Q_{sh\ max}$, $Q_{sh\ min}$ and Q_{sh} (W) are, respectively, the maximum and the minimum heat production and sensible emission of heat by the animal's body, in conditions of standard metabolism, within the thermally neutral area.

By transition to specific values of q_{sh}, we obtain:

$$\frac{Q_{sh\ max}}{F_{sa}} > q_{sh} > \frac{Q_{sh\ min}}{F_{sa}}, \tag{2}$$

where F_{sa} is animal body surface (m^2).

The second convenience condition defines the permissible temperature values of heated and cooled surfaces in close vicinity to, or contacting with, the animal, i.e., those participating in the heat exchange with it.

For conditions under consideration, there is a certain correlation between the sensible heat emission Q_{sh} and animal body surface temperature t_{sa}: $t_{sa} \leftrightarrow Q_{sh}$ [35].

Within the borders of the basic heat exchange between the animal body and the environment, there exist intervals of sensible temperature of animals $\{t_{max} \ldots t_{min}\}$ and those of their specific heat emission $\{q_{sh\ max} \ldots q_{sh\ min}\}$. Therefore, within the above-mentioned intervals, any value of heat production corresponds to a certain temperature value.

It follows that temperature t_{hs} on the heated surface where animals are located, and that of the animal skin t_{sa}, for the area of the basic heat exchange, have to comply with the condition $t_{sa} \approx t_{hs}$.

Mathematical formulation of the thermal balance and heat fluxes transfer in general terms has the following form:

$$Q_{tp} = q_{sh} F_{pa} - Q_{fs} - Q_{con'} - Q_{rad'}, \quad (3)$$

where Q_{tp} (W) is the heat flux required for maintaining the target temperature value on the heating panel surface t_{hs} (°C); F_{pa} is the surface area of the panel occupied by animals (m^2); F_p is that of the bottom surface of the panel facing the floor (m^2); ($F_p - F_{pa}$) is the part of the heating panel surface not occupied by animals (m^2); t_f is floor temperature in the premises (°C); q_{sh} is the specific heat flux entering the panel from animals through the surface contacting with the panel (W/m^2); Q_{fs} (W) is the heat loss by thermal conductance through the bulk of the floor (Formula (11)); $Q_{con'}$ and $Q_{rad'}$ (W) are, respectively, heat loss via convection and radiation from the part of the heating panel surface ($F_p - F_{pa}$) not occupied by animals in the premises.

While determining the value of the heat flux Q_{tp} required for maintaining the target panel temperature, heat transfer coefficient k_{htr} ($k_{htr} = \lambda_{ins}/\delta_{ins}$) and floor temperature in the premises t_f were chosen as the essential variables [36].

In order to maintain the required temperature on the surface of the panel, for prenursery pigs of the age from 1 to 4 weeks, the heat flux from an external source (floor-mounted heated panel) has to be varied in the range of 0 to 190 W, for the chosen values of heat transfer coefficient and floor temperature (Figure 1). Sign 'plus' on Z-axis corresponds to panel heating from external sources and heat transfer to prenursery pigs, while, contrariwise, sign 'minus' means panel cooling and heat transfer from animals.

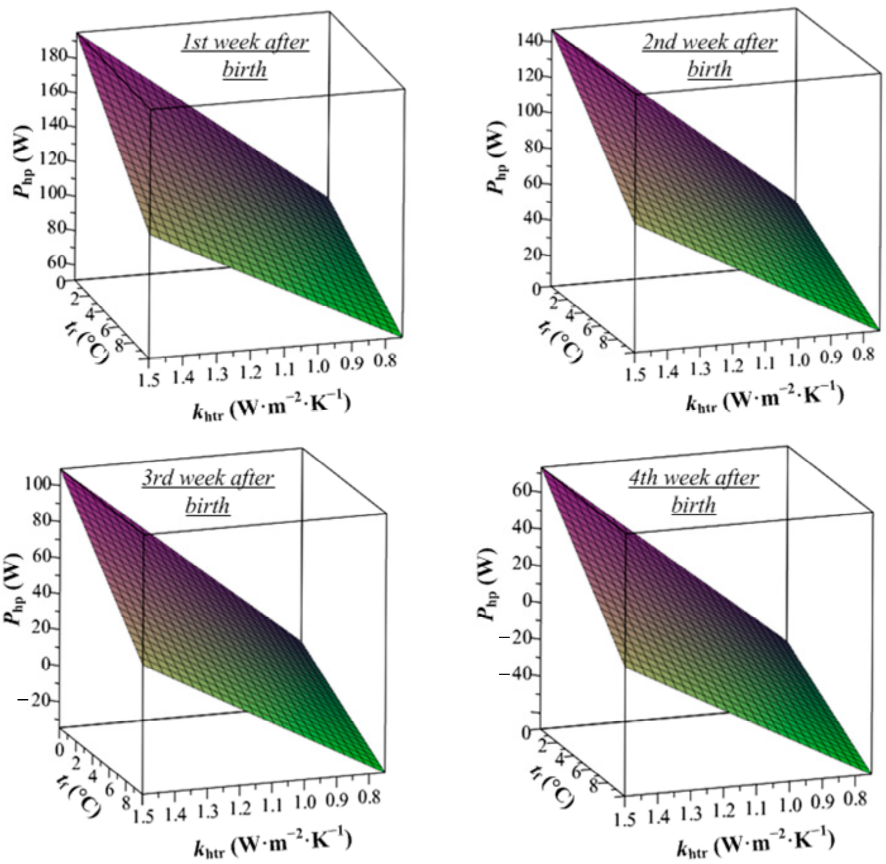

Figure 1. Required power capacity P_{hp} of floor-mounted heating panels depending on the floor temperature t_f, heat transfer coefficient $k_{htr,}$ and age of prenursery pigs.

In the general form, such representation is defined by the relationships between the design parameters and energy-related parameters of technical aids used for local heating, for maintaining the required thermal conditions in areas where animals are kept.

Thermoelectric heat pumps, on the basis of Peltier elements, do not contain moving parts and they are capable of withstanding shocks and vibrations, retaining operability in humid air conditions and in corrosive environments. They are environmentally benign and exhibit high operation reliability and durability. These devices have come into use in the high-technology processes of various industry fields [37–39] and in agriculture [40].

2.2. Block Diagram for Floor-Mounted Heating Panel with Thermoelectric Heat Pump

A block diagram of the energy-saving installation, implementing a floor-mounted local heating system for prenursery pigs with the application of thermoelectric effect, (Figure 2) has been designed [33].

The local heating installation for prenursery pigs comprises thermoelectric assembly including a dedicated number of Peltier elements 4, air heat-exchanger 2 at the cold side of Peltier elements 4, with extractor-type fan 3 installed in the air duct of the cold circuit 1. The latter is connected to the exhaust air ventilation system 6 of the swine house. At the hot side of Peltier elements, water heat-exchanger 5 is installed and connected to the air circuit duct 10 at the hot air circuit, via circulation heat pump 11, with heating panel 8. Water heated in heat-exchanger 5 is used as the heat-carrier. Temperature sensor 9 measures the surface temperature of heating panel 8. Thermal capacity of the thermoelectric assembly is controlled by varying electric current flowing through Peltier elements 4. Power supply, monitoring, and control functions are performed by control module 7.

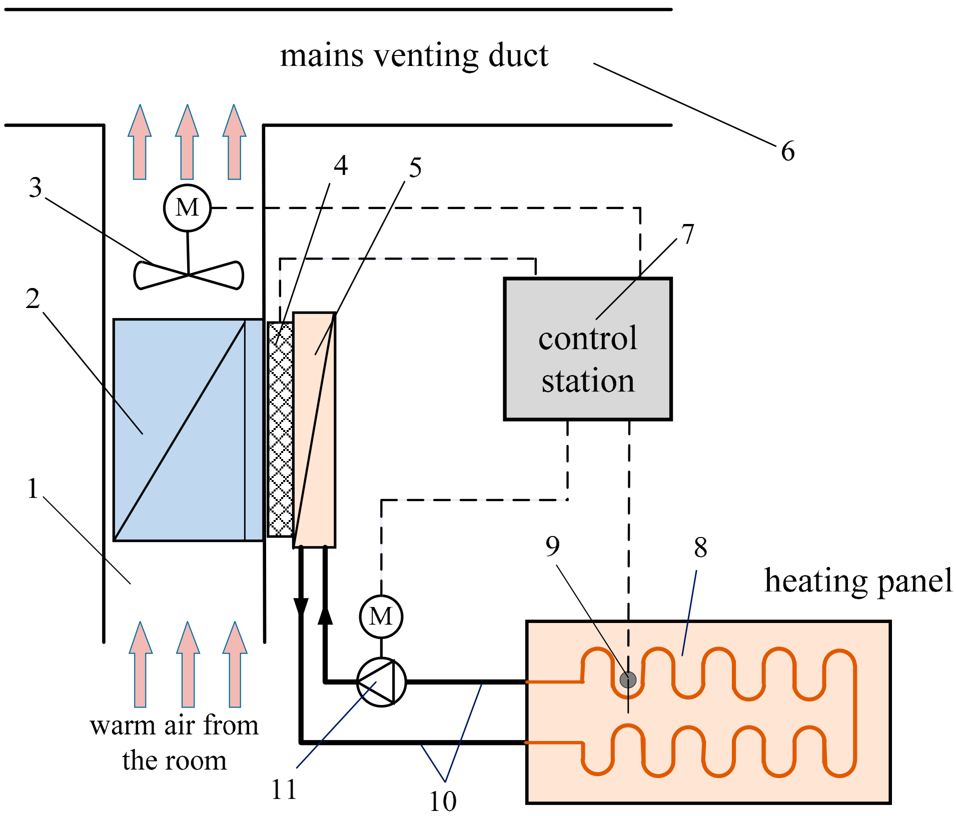

Figure 2. Block diagram of local floor-mounted heating installation for prenursery pigs with the application of thermoelectric effect: 1—duct of the cold air circuit; 2—air heat-exchanger at the cold side of Peltier elements; 3—electric fan; 4—Peltier elements; 5—water heat-exchanger at the hot side of Peltier elements; 6—mains venting duct; 7—control module; 8—floor-mounted heating panel; 9—temperature sensor; 10—duct of the hot air circuit; 11—circulation heat pump.

In accordance with the technological design standards for pig-breeding farms and enterprises, the volume of intake air supplied to the premises has to be defined with an account of heat absorption, moisture elimination, and gaseous air pollutants. At the same time, it must not be less than 30 m^3/h during the cold season, and not less than 45 m^3/h during mid-seasons per 100 kg of animal body weight. Premises of pig-breeding farms have to be equipped with air intake ventilation, based on the conditions of calculated parameter provisions for internal air. The air velocity in the piglets' locations should not exceed 0.2 m/s [4].

In compliance with the technological diagram shown in Figure 1, installation of local floor-mounted heating for prenursery pigs has to be connected to the main exhaust ventilation system 6 of the pig-breeding premises, via the air duct of the cold air circuit. A certain amount of heat from the used-up exhaust air transferred from the premises is directed to the water heat-exchanger 5 at the hot side of assembly, where the liquid heat-carrier (water) gets additionally heated, via air heat-exchanger 2 at the cold side of the thermoelectric assembly and Peltier elements 4. Therefore, the thermoelectric assembly operates in the mode of heat pump.

2.3. Calculating Thermal Parameters of the Heating Panel

The capacity of the heating device designed to provide the required temperature on the surface of the heated panel will compensate its thermal loss into the environment.

Deduced from the conditions of a quasi-stationary state, the thermal energy balance for the heating surface area not occupied by animals has the following form:

$$Q = Q_{hs} + Q_{ss} + Q_{fs}, \tag{4}$$

where Q_{hs} (W) is heat loss via convection and radiation from the upper surface of the heated panel into the premises; Q_{ss} (W) is thermal output from the side surfaces of the panel; Q_{fs} (W) is heat loss by thermal conductance through the bulk of the floor, i.e., into the ground (Figure 3).

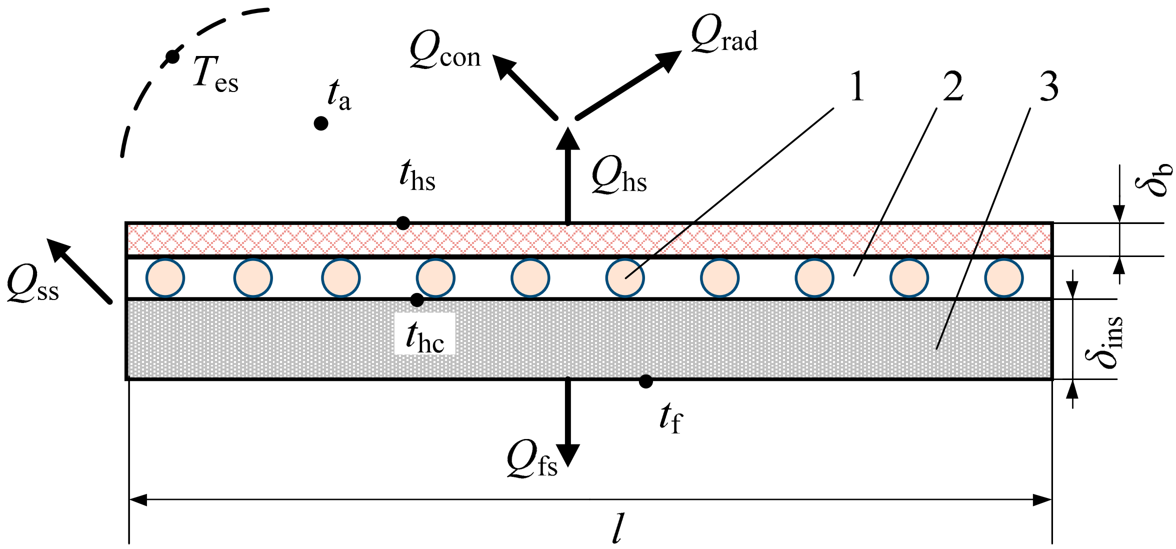

Figure 3. Diagram for calculating thermal capacity of the heating panel: 1—substrate; 2—heat-carrier; 3—thermal insulation.

The value of the heat transfer convective component is defined from the following known formula:

$$Q_{con} = \alpha_{con} F_{hs} (t_{hs} - t_a), \tag{5}$$

where t_a (°C) is air temperature in the premises; α_{con} ($W \cdot m^{-2} \cdot K^{-1}$) is the convection heat transfer coefficient of the panel surface; t_{hs} (°C) is the required temperature on the surface of the heating panel; F_{hs} (m^2) is the area of the heat-emitting surface.

These parameters have to be chosen in compliance with the technological design standards for agricultural animal-breeding sites [4].

The dimensions of the area for prenursery pigs managed in gestation crates with tier breeding sow may vary depending on the dedication of the particular pig-breeding farm. Normally, its surface area F_{ps} is in the range of 0.5 m^2 to 1.5 m^2.

In accordance with the technological requirements, value t_a will be maintained in the range of 22 °C to 28 °C (for premises with post-weaning pigs and sow houses). Value t_{hs} will be in the range of 32 °C to 35 °C. The rate of air motion v_a in areas where animals are located shall not exceed 0.2 m/s ($v_a \leq 0.2$ m/s) [4].

Reynolds number is

$$\mathrm{Re} = \frac{v_a l}{v_a}, \quad (6)$$

where l is length of the heating panel (characteristic dimension, m); v_a (m/s) is air velocity; v_a (m^2/s) is air kinematic viscosity.

Convection heat transfer coefficient in the laminar boundary layer [41] equals to:

$$\alpha_{con} = 0.33\left(\frac{\lambda}{l}\right)\mathrm{Re}^{0.5}\mathrm{Pr}^{1/3}, \quad (7)$$

where λ ($W \cdot m^{-1} \cdot K^{-1}$) is air thermal conduction coefficient.

Radiant heat flux from the heating panel is:

$$Q_{rad} = c_0 \varepsilon_{hs} F_{hs}\left[\left(\frac{T_{hs}}{100}\right)^4 - \left(\frac{T_{es}}{100}\right)^4\right], \quad (8)$$

where c_0 = 5.76 $W \cdot m^{-2} \cdot K^{-1}$ is blackbody coefficient; ε_{hs} is the total emissivity of the heating panel surface; F_{hs} (m^2) is surface area of the heating panel; T_{hs} and T_{es} (K) are, respectively, surface temperatures of the heating panel and the cladding structures inside the premises.

Total heat emission from the heating panel surface due to the convective and radiant heat exchange is equal to:

$$Q_{hs} = Q_{con} + Q_{rad}. \quad (9)$$

Heat-carrier temperature can be defined as:

$$t_{hc} = t_{hs} + Q_{hs}\frac{\delta_b}{\lambda_b \cdot F_{hs}}, \quad (10)$$

where t_{hs} (°C) is temperature of the heating panel (substrate) surface; δ_b (m) is substrate thickness; λ_b ($W \cdot m^{-1} \cdot K^{-1}$) is the thermal conduction coefficient of substrate material.

Heat loss from the side surface Q_{ss} of the heating panel can be ignored considering its small surface area.

Preliminary calculation for thermal energy loss from the heating panel through the floor Q_{fs} has to be performed accounting for a number of assumptions:

- in cold seasons, floor temperatures will be higher than water freezing point and dew point,
- the heated panel does not have any effect on the thermal state of the floor where it is mounted,
- floor temperatures are assumed to be lower than their calculated values by 5 °C to 10 °C, in order to ensure system stability.

Heat flux into the balk of the floor (ground) due to thermal conductance is as follows:

$$Q_{fs} = \frac{\lambda_{ins}}{\delta_{ins}} F_p (t_{hc} - t_f), \quad (11)$$

where λ_{ins} ($W \cdot m^{-1} \cdot K^{-1}$) is thermal conduction coefficient of the thermal insulation; δ_{ins} (m) is thickness of the thermal insulation layer; t_{hc} and t_f (°C) are, respectively, temperatures of the heat-carrier and of the floor.

Table 1 presents calculation results for the heating panel capacity performed for limiting temperature and air velocity values, in premises for managing prenursery pigs.

Table 1. Calculation for heating panel power capacity.

Parameter	Designator	Unit	Value
Air temperature in premises	t_a	°C	18
Temperature on the heating panel surface	t_{hs}	°C	30
Relative air velocity in premises	v_a	m/s	0.2
Heating panel length	l	m	1.0
Upper surface area of the heating panel	F_{hs}	m^2	0.7
Air kinematic viscosity	υ	m^2/s	14.7×10^{-6}
Air thermal conduction coefficient	λ	$W \cdot m^{-1} \cdot K^{-1}$	2.49×10^{-2}
Reynolds number	Re		13,605
Convection heat transfer coefficient	α_{con}	$W \cdot m^{-2} \cdot K^{-1}$	0.86
Convection component of the heat flow from the panel surface	Q_{con}	W	6.5
Total emissivity of the panel surface	ε_{hs}		0.92
Temperature of the heating panel surface	T_{hs},	K	303
Temperature of the cladding structure	T_{es}	K	283
Radiant component of the heat loss	Q_{rad}	W	73.1
Total thermal energy loss from the heating panel surface	Q_{hs}	W	79.6
Substrate thickness	δ_b	m	0.003
Substrate material thermal conduction coefficient	λ_b	$W \cdot m^{-1} \cdot K^{-1}$	0.05
Heat-carrier temperature	t_{hc}	°C	35.7
Insulation material thermal conduction coefficient	λ_{ins}	$W \cdot m^{-1} \cdot K^{-1}$	0.04
Thickness of the thermal insulation layer	δ_{ins}	m	0.04
Floor temperature	t_f	°C	5
Heat loss through the floor	Q_{fs}	W	21.5
Calculated power capacity	P_{hp}	W	101.2

3. Results and Discussion

Based on the calculation results for the heating panel capacity (Table 1) and physically modeling the heating process for the floor-mounted panel [33] with the application of thermoelectric Peltier elements, and with the account of the data reported in [42,43], an experimental sample of the floor-mounted heating panel power capacity 100 W for prenursery pigs has been manufactured in compliance with the technological block diagram shown in Figure 1. The heating panel operates in the mode of heat pump (Figure 4). Technical parameters of the installation are presented in Table 2.

Table 2. Basic parameters of experimental sample heating panel.

Parameter	Unit	Value
Peltier element type	-	TEC1-12706
Peltier element output power	W	50
Number of Peltier elements	pcs	2
Peltier battery power consumption	W	98
Peltier battery input voltage	U	12
Heat-carrier circulation flow rate	L/h	36.8
Panel weight	kg	5
Dimensions: length × width × thickness	m	1.0 × 0.7 × 0.05
Panel surface area	m^2	0.7

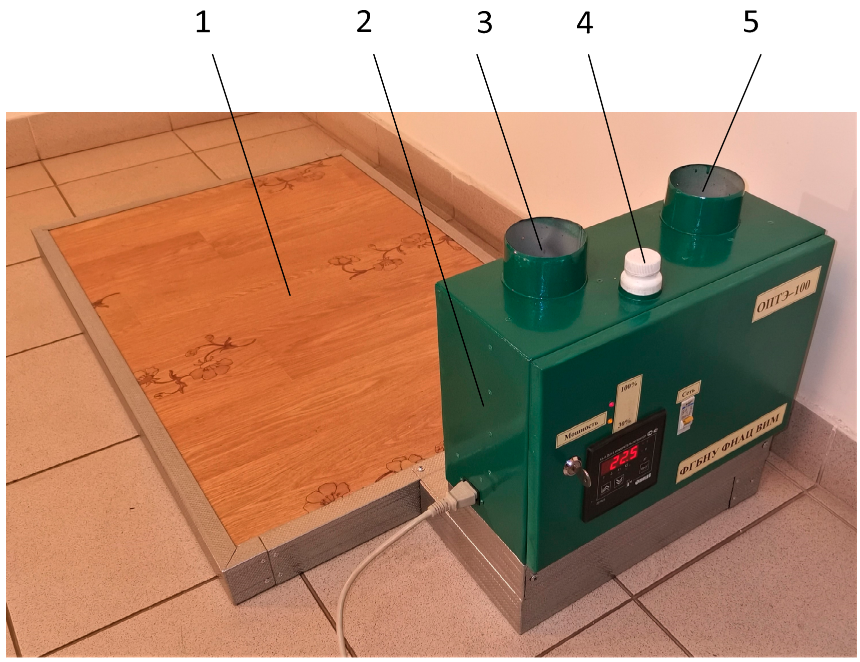

Figure 4. Outlay of the heating panel: 1—floor-mounted heating panel; 2—control panel; 3—air intake; 4—heat-carrier tank; 5—exhaust air pipe.

Test Results of the Experimental Sample of the Heating Panel

Within the frame of this work, experimental studies of the thermal parameters of the floor-mounted heating panel for prenursery pigs have been carried out. The following two operation modes of the installation were studied: without animals, and with prenursery pigs with 70% charging of the crate. Air temperature inside the premises was $t_a = 18 \pm 1$ °C, which complies with the recommendations given in [4] for combined managing of breeding sows and prenursery pigs, for instance, in a sow house.

The laboratory stand for automated measurement, visualization and registration of the obtained data has been developed for conducting experimental studies. The laboratory stand contains: Multichannel temperature control device UCT-38 (accuracy class 0.5); temperature sensors (thermocouples chromel-copel type with an operating temperature range of 50 °C to 300 °C, accuracy class 0.5); a single-phase electric energy meter (accuracy class 1.0); thermal camera Uni-t Uti260b.

Experimental studies of the installation were carried out during the winter season, starting from January to the middle of February. Heat-carrier temperature t_{hc_exp} was measured, in the input (t_{in}) and in the output (t_{out}) of the heating panel. Temperature on the surface of the heating panel t_{hs_exp} was registered in a number of selected specific points. Uniform character of the temperature distribution over the heating panel surface was observed (the maximum temperature deviation was 0.5 °C). In the course of experimental studies, the electrical energy consumption by thermoelectric assembly was measured with the use of an electric energy meter.

Thermal power consumed to supply the floor-mounted heating panel is determined by Formula (12), for selected values of the heat-carrier specific thermal capacity. The difference between the values of power consumed by the panel and the actual power of the installation represents the available thermal power collected from the ventilating air. Measurement results for thermal parameters of the floor-mounted heating panel were processed with the application of probabilistic method.

The temperature of the upper surface of the floor-mounted heating panel t_{hs_exp}, regardless of the piglets' location, is maintained in the range of 29 . . . 32 °C with the help of the heat regulation unit,, which controls the output power of Peltier elements. This changes the temperature of the heat-carrier (water) circulating along the closed hot loop comprising the waterой heat-exchanger at the hot side of the Peltier elements, floor-mounted heating panel, hot circuit pipeline and circulating heat pump.

A temperature diagram for the heat-carrier that enters the panel at temperature t_{in} and has the temperature t_{out} in the output from the panel is shown in Figure 5, for air temperature in premises t_a = 18 ± 1 °C. Acording to the results of experiments, the integral mean difference between heat-carrier temperatures in the input and output of the heating panel is (2.7 ± 0.2) °C.

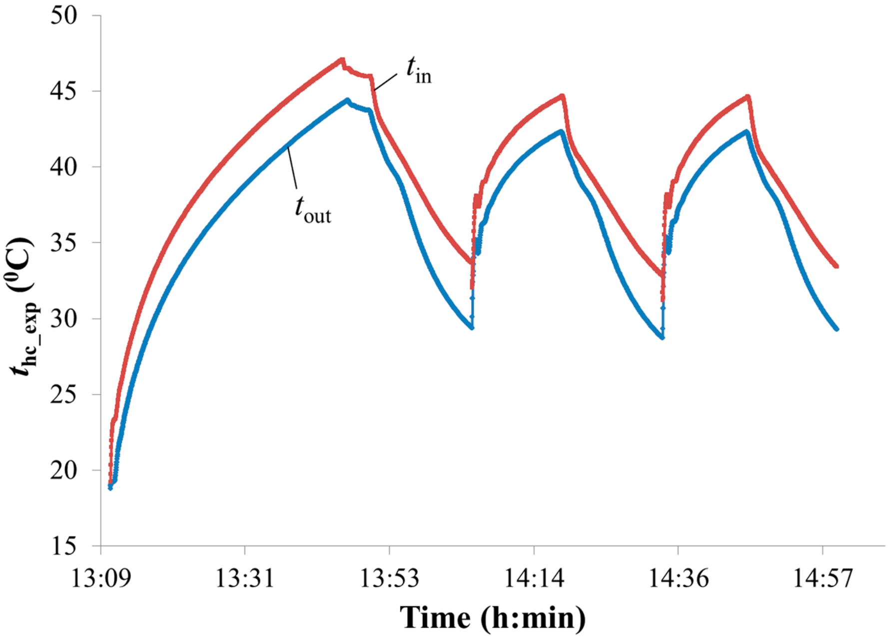

Figure 5. Temperature of the heat-carrier t_{hc_exp} in the input into the panel t_{in} and in its output t_{out}.

Thermal power P_{hp}, consumed for the heating panel is:

$$P_{hp} = \frac{G_{hc} c_t (t_{in} - t_{out})}{3600}, \quad (12)$$

where G_{hc} (L/h) is heat-carrier flow rate; c_t (J·kg^{-1}·K^{-1}) is the specific heat capacity of water.

Replacing the variables with their numeric values in Formula (12), for c_t = 4200 J·kg^{-1}·K^{-1}, we obtain the value of the thermal power spent heating the panel equal to 116 W, which is by 18 W greater than that consumed from the Peltier elements circuit (98 W) measured in experiments. Thus, the energy-saving effect is 15%, for the above conditions. This is achieved owing to the partial heat recuperation of the exhaust ventilating air.

Therefore, the thermoelectric assembly operates in the mode of a heat pump [44], and a certain share of thermal energy (equal to 18 W) collected from the air in the exhaust ventilation of the premises (Figure 1) having temperature t_a = 18 °C is used to heat water in the panel, contributing to the energy efficiency of the newly designed installation.

The thermoelectric assembly operates in the heat pump mode and part of the thermal energy in the amount of 18 . . . 22 W, taken from the exhaust ventilating air from the room, is used for additional heating of the heat-carrier. A thermoelectric floor-mounted heating panel consumes 15–20% less electricity when creating the same power on the heating surface, compared to other electric heaters (mats, IR lamps, etc.). A preliminary feasibility study showed that the payback period for the heating panel will be 2–3 of the year. The economic effect is achieved by reducing operating costs (electricity costs). The use of a floor-mounted heating panel can also help reduce the mortality of prenursery pigs under 4 weeks of age.

Graphs (Figure 6) show experimental data on the heating panel surface temperature t_{hs_exp} without animals and for 70% charging of the crate with prenursery pigs. The control system of the floor-mounted heating panel maintains the temperature on its surface, in a stationary state, with a reasonable accuracy of ±0.5 °C.

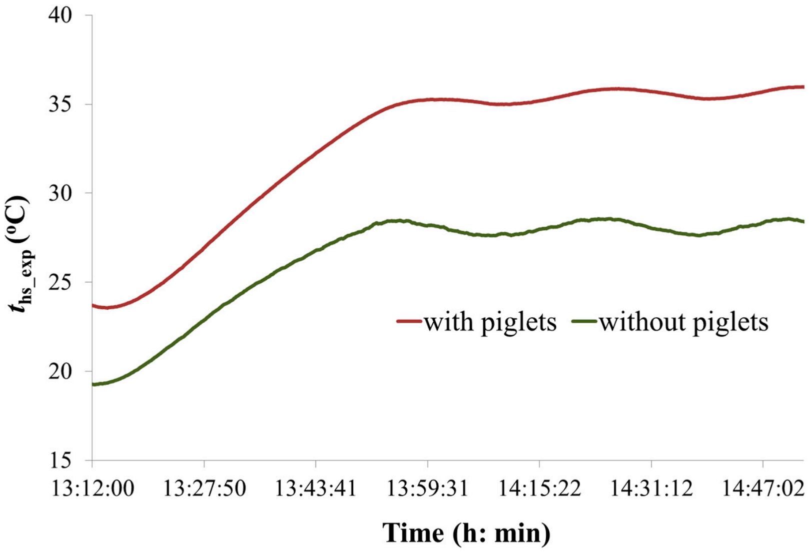

Figure 6. Surface temperature t_{hs_exp} of the floor-mounted heating panel without animals and at 70% charging of the crate with prenursery pigs.

Based on calculation results of the floor-mounted heating panel parameters (see Table 1) and the physical modeling of the installation [33], as well as in accordance with the block diagram (Figure 2), an experimental sample of the floor-mounted heating panel for piglets was made using thermoelectric modules, operating in heat pump mode. The main values of the calculated parameters of the heating panel correspond to the results obtained during the experimental studies (Table 3).

Table 3. Comparison of calculated and experimental parameters.

Parameter	Unit	Value	
		Calculated (Initial Requirements)	Experimental (Average)
Installation power consumed from the electric network	W	100	98
Heat recuperation	W	15	18
Installation supply voltage	U	220	219
Heat-carrier circulation flow rate	L/h	35.0	36.8
Heating panel surface temperature without animals	°C	30.0	29.0
Heating panel surface temperature when filled with animals	°C	-	35.0
Heat-carrier temperature at the panel inlet	°C	41.7	42.0
Heat-carrier temperature at the panel outlet	°C	38.7	39.3

4. Conclusions

A physical model of heat transfer in the system 'animal-environment' has been discussed. The borders of the variation range for the heat flux of the floor-mounted heating panel, designed to ensure animal-friendly conditions for prenursery pigs of various age groups, have been determined. It has been calculated that, for the selected standard values of heat transfer coefficient k_{htr} = 0.8 … 1.5 W·m^{-2}·K^{-1} and floor temperature t_f in the range from 0 to 10 °C, thermal capacity of the floor-mounted heating panel should vary in the range of 0 to 190 W, in order to provide a friendly environment for prenursery pigs of ages one to four weeks.

As a result of the studies carried out, the effectiveness of the designed energy-saving floor-mounted installation for local heating prenursery pigs, with the application thermoelectric assembly operating in the mode of heat pump, has been theoretically substantiated and experimentally confirmed. Its scientific novelty has been proved by patenting (RU 2743814 C1).

An experimental sample of the installation having thermal capacity 116 W (for the following conditions: $k_{\mathrm{htr}} = 0.9 \ldots 1\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ and $t_{\mathrm{f}} = 5\ ^{\circ}\mathrm{C}$ to $6\ ^{\circ}\mathrm{C}$) for local heating of prenursery pigs managed in gestation crates has been designed, and its laboratory tests have been carried out. Results obtained in the course of studies confirmed a rather high level of energy-saving (approx. 15% compared to conventional solutions for local heating prenursery pigs.) of the developed equipment that was achieved owing to the partial recuperation of heat of the exhaust ventilating air.

The results of the research carried out can be the basis for further development and optimal operating mode selection for energy-saving thermal equipment employing thermoelectric Peltier elements.

Further studies will be focused on the energy efficiency enhancement of the thermoelectric installation by optimization of the thermoelectric heat pump operating modes.

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