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EXPERIMENTAL STUDIES OF THE AIR FLOW HEATING PROCESS IN A VERTICAL SOIL HEAT EXCHANGER

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The article considers the possibilities of using the soil as a source of low-potential heat in Ukraine, where it maintains a constant temperature at a depth of more than 10 meters +9…12 °C throughout the year. This creates favorable conditions for efficient use of heat pumps. The analysis of technical means of extracting thermal energy from the surface layers of the soil shows that vertical soil heat exchangers are the most effective for achieving the required parameters of the microclimate in livestock premises.

The study of the process of heating the air flow in the vertical soil heat exchanger was carried out under production conditions at the pig farm of the Agrofirma Napadivska Agricultural Company in the Vinnytsia region. To increase the efficiency of the clean air injection system, a U-shaped vertical soil heat exchanger is installed, which is connected to the ventilation system of the pig fattening room.

Research was conducted at different levels of air flow (200, 500, 800 m³/hours) and air temperature in the soil heat exchanger, which was fixed six times a day. Indicators of climatic conditions were determined by measuring temperature and air humidity, as well as by monitoring temperature dynamics throughout the year.

According to the results of experimental studies of the process of heating the air flow in a U-shaped vertical soil heat exchanger in production conditions, the dynamics of temperature changes throughout the year were determined. The obtained regression equations of the second order of changes in air flow temperature ΔT_a and effective heat capacity N_E from temperature T_{in} and expenses Q_{in} air flow at the entrance to the U-shaped vertical soil heat exchanger.Statistical comparison of experimental data with theoretical dependence by the Pearson correlation coefficient – 0,95 and Fisher's test – $F = 1,93 < F_m = 2,98$ indicates the high adequacy of theoretical dependencies.

Key words: *microclimate, temperature, humidity, animal husbandry, air heating, soil heat exchanger, heat exchange, air flow, heat transfer, energy efficiency, heat exchange parameters, temperature regime.*

Eq. 2. Fig. 6. Table. 1. Ref. 18.

1. Problem formulation

Global trends towards rising prices for traditional fuel resources used to generate electricity require agricultural sector enterprises to take measures to diversify sources of electricity supply and increase the level of energy autonomy. Despite the existing general opinion regarding the low efficiency of the implementation of wind and solar energy in the natural and climatic conditions of Ukraine, the experience of highly developed countries says otherwise:

– the implementation of projects related to the implementation of autonomous energy supply systems for agro-industrial complex enterprises based on SES and wind turbines has environmental and economic advantages over traditional electricity supply;

– the modern development of technologies allows the conversion of solar and wind energy into electric energy in territories that were previously (20-30 years ago) considered unsuitable for this type of energy [1].

The development of the organic sector is particularly important and promising for domestic farmers, consumers and the state as a whole, especially in the context of ensuring food security, healthy nutrition and preservation of the natural environment. According to strategic goal 1 "Ensuring a stimulating and advisory agrarian policy" of the Strategic Policy Course in the field of development of the agro-industrial sector, one of the ways to achieve the strategic goal is to support organic production. Another way to achieve the goal is to ensure the development of sustainable production, where the task for the Government is to encourage sustainable agricultural production, protect the environment and animals, spread the use of organic production methods and the use of biotechnology, "climate-smart" agriculture and forestry with a reduction in greenhouse gas emissions gases and adaptation to climate change, sustainable management of natural resources and preservation and increase of biodiversity [2].

In industrial animal husbandry, the creation of an optimal microclimate depends on many factors and is carried out through a number of compromises. Currently, there are data on the basis of which it is possible to accurately establish those environmental factors that are necessary for the manifestation of genetically determined abilities of animals. However, providing a thermally neutral zone is associated with large capital investments, high energy prices, and recently requires increasingly high operating costs. As long as there are no significant shifts in pricing, instead of forming a thermoneutral zone, it is advisable to create an optimal productive environment, which is a compromise between high production costs and the quantity and quality of livestock products. Given that the size of capital investments and operating costs can change significantly within a short time, the microclimatic conditions characteristic of an optimal productive environment cannot remain unchanged either, even considering the fact that the requirements of animals to their environment practically do not change during a long time Air quality and the quality of the microclimate in the livestock premises can be characterized by the concentration of pollutants (e.g. ammonia, dust and bacteria), as well as the temperature, humidity and air velocity in the animal area, since high concentrations of pollutants and high temperatures have a negative effect on animal health and performance. Too low air temperatures or high air velocities in the animal housing area also have a significant impact on animal health, behavior and performance, especially for weaned piglets. The air in the livestock premises contains pollutants, moisture and heat emitted by animals, feed, floor surfaces and manure. Contaminated air, moisture and heat are removed through ventilation. The ventilation system ensures the distribution of fresh air in the building. It is necessary to have a good understanding of the efficiency with which different ventilation systems remove pollution and heat. Improving the efficiency of ventilation is an important strategy for reducing pollutant concentrations in animal housing [3-5].

In most of Ukraine, the most accessible source of low-potential heat is the soil. At a depth of more than 10 meters, it maintains a constant temperature in the range of +9…12 °C throughout the year. This creates favorable conditions for efficient use of heat pumps. Ukraine has a significant potential for using soil heat and groundwater [6]. The temperature of the soil and rocks on the Earth's surface depends on the balance of thermal energy coming from the Sun and thermal radiation from the Earth's surface. Thermal energy coming from the Sun accumulates in the soil layer of sedimentary and rock at depths to the isothermal surface. This soil layer can be considered as a natural seasonal thermal energy accumulator, since the energy withdrawn in the winter period is restored in the summer. This also applies to groundwater, which saturates the topsoil and sedimentary rocks [7].

The analysis of technical means of extracting thermal energy from the surface layers of the soil [8–10] made it possible to establish that to achieve the necessary parameters of the microclimate in the premises for animals, vertical soil heat exchangers are the most effective among the considered options. However, their optimal parameters, location and limits of energy efficiency are not sufficiently covered in the literature.

Based on the analysis of previous studies on the structural and technological scheme of the soil-air heat exchanger, we will consider two options that are the most economical from the point of view of their manufacture. The first option is based on research [11, 12] – a concentric vertical soil heat exchanger. What is more, the design and technological parameters were chosen precisely those obtained by the results of experimental studies. The second option is more classical – a U-shaped vertical soil heat exchanger [13, 14] (Fig. 1).

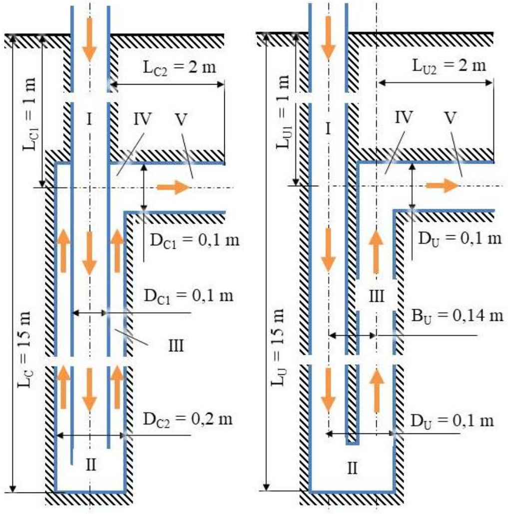


Fig. 1. Calculation diagram of a U-shaped vertical soil heat exchanger

According to research [15] (the carrier was water), the concentric heat exchanger is the most effective for short-term operation, however, during long-term operation, its efficiency decreases by 18–20%. In addition, our own research experience of concentric heat exchangers [16] demonstrates that the concentric arrangement of the pipe in the pipe leads to a secondary temperature change through the internal walls. This negatively affects the process of heating or cooling the air flow in the soil. Note that thermal insulation of the internal walls creates a sufficiently large non-working zone, which leads only to pneumatic losses.

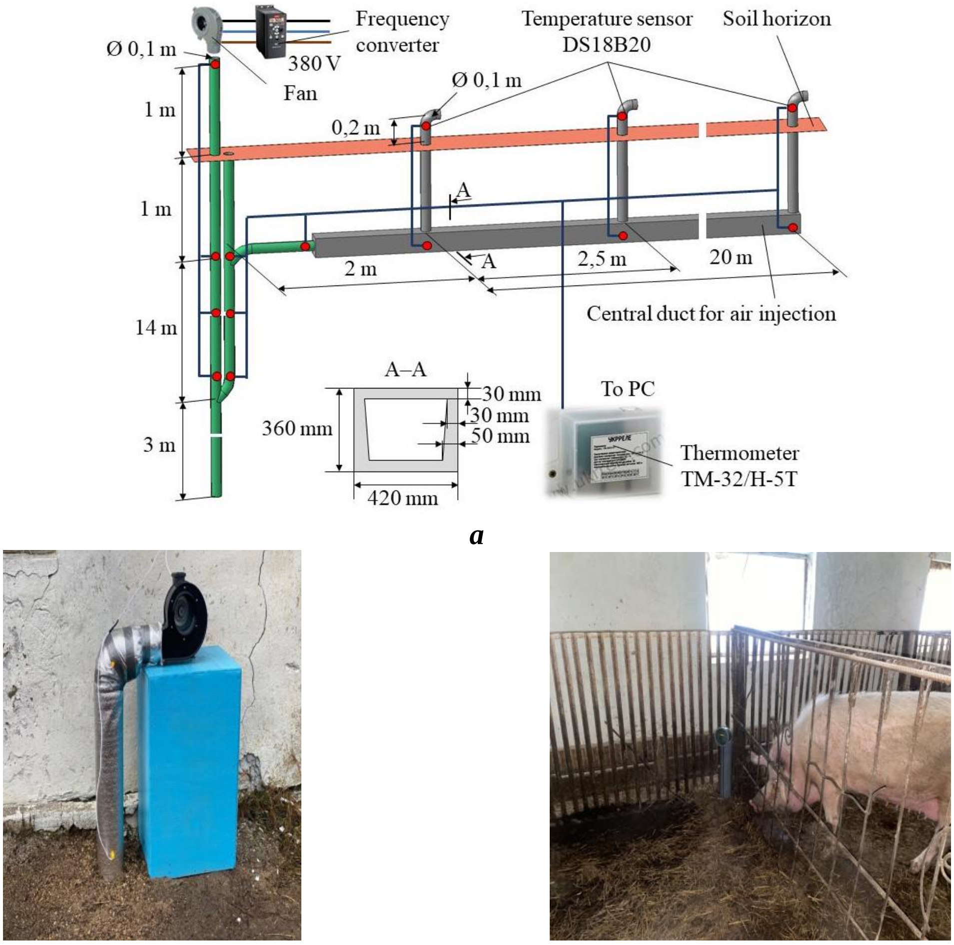
According to the results of the previous numerical simulation in the software package Simcenter Star- CCM+ [17] it was established that the effective heat capacity of the concentric heat exchanger is $N_{EC}(T_{in} = 31{,}7\ °C) = 1266Vt$, $N_{EU}(T_{in} = -12{,}2\ °C) = 1052\ Vt$ less than the effective heat capacity of the U- shaped heat exchanger $N_{EU}(T_{in} = 31{,}7\ °C) = 1575\ Vt$, $N_{EU}(T_{in} = -12{,}2\ °C) = 1235\ Vt$. That is, a U-shaped vertical soil heat exchanger is 17-24% more efficient than a concentric one.

2. Analysis of recent research and publications

The study of the process of heating the air flow in the vertical soil heat exchanger was carried out in production conditions at the pig farm of the Agrofirma Napadivska Agricultural Company (Vinnytsia region). In one of the premises for fattening pigs, since 2010, ventilation of the ground channel has been used (Fig. 2).

To increase the efficiency of the clean air injection system and to conduct experimental studies, a U-shaped vertical soil heat exchanger was installed behind the pig fattening room. The outlet pipe of the soil heat exchanger is connected to one of the lines of the clean air injection system at a depth of 1 m from the soil surface. The total length of the well is 18 m. At a depth of 3 m, the duct was thermally insulated. The last 3 m are made to collect condensed water. The structural and technological scheme and the general view of the experimental installation are shown in fig. 2 (a, b, c).

Indicators of the climatic conditions of the research were determined based on the data of temperature and air humidity measurements at the beginning of each series of measurements and entered into an Excel data table.



a

b *c*

Fig. 2. Scheme (a) and general views of the soil heat exchanger (b) and ventilation of the ground channel of the premises for fattening pigs (c)

The process of heat extraction from the soil massif is influenced by: type and moisture of the soil, operating time of the geothermal ventilation in a certain mode (heating or cooling of the supply air), outside air temperature, volume injection of air, diameter, length, number, interaxial distance and location of soil heat exchangers.

The type of soil is low-humus chernozem, on which the pig farm is located.

The geometric dimensions are selected from theoretical calculations and shown in fig. 2, a. A DUNDAR CT 16.4 centrifugal fan was used as a power air unit (maximum air flow– 850 m^3/hour).

Research is carried out by varying the values of the following factors:

– air flow on 3 levels, minimum (200 m^3/hour), medium (500 m^3/hour) and maximum (800 m^3/hour), which are determined after calibration by the speed of rotation of the electric motor of the fan, are regulated by the frequency converter FC 51 of the VLT Micro series (current frequency 10; 30; 50 Hz) under the condition of stable operation at the specified frequency; air flow was measured with a Solomat MPM 500E multifunctional device;

–the air temperature in the soil heat exchanger was fixed and recorded 6 times a day.

The central duct for pumping air at the fattening pig farm of Agrofirma Napadivska was laid at the construction stage and was a tray of engineering networks L 1-8/2 (Fig. 2, a), which passed under the piggery. The nozzles for air injection, which came out of the central air duct, were polypropylene pipes (Fig. 2).

DS18B20 digital temperature sensors are placed throughout the air injection system, which are connected to the TM-32/N-5T Thermometer data recording system. The distance between the sensors in the soil heat exchanger was 3 m along the entire duct.

The research was conducted in the period from 02.01.2021 to 02.01.2022.

During the research, the temperature dynamics obtained from each sensor for the entire time of the research was recorded.

The power of the centrifugal fan motor was determined by the frequency converter.

For typical low (winter), high (summer) and average (autumn and spring) temperatures T_{in} variation was carried out by injecting the air flow Q_{in}.

The research criteria were chosen to change the temperature of the air flow at the inlet and outlet of the soil heat exchanger ΔT_a. To optimize the parameters of the soil heat exchanger, the criterion - heat capacity was used N_E.

3. The purpose of the article

The purpose of the study is to determine the dependence of the change in the effective heat capacity of the U-shaped vertical soil heat exchanger N_E from the flow and temperature of the incoming air.

4. Results of the researches

According to the results of experimental studies of the process of heating the air flow in

U-shaped vertical soil heat exchanger in production conditions on a pig farm PPP "Agrofirma Napadivska" (Vinnytsia region) established the dynamics of temperature changes during 2022. Figure 3 shows the dynamics of temperatures in the soil heat exchanger at different distances from the duct L_a. The absolute value of the temperature difference at the inlet and outlet of the soil heat exchanger is also noted Δ.

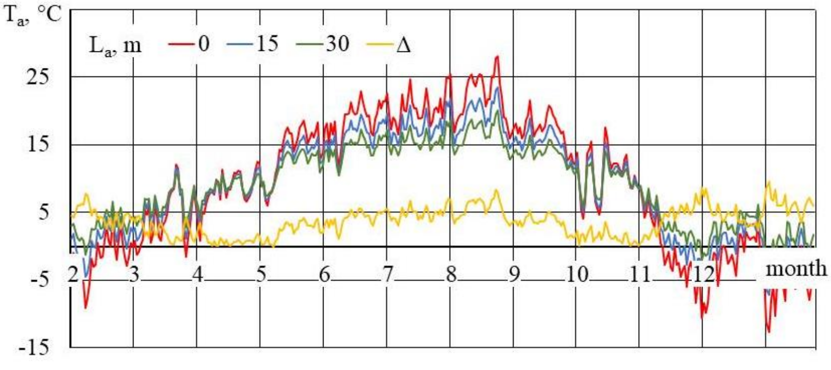


Fig. 3. Dynamics of temperatures in the soil heat exchanger at different distances of the duct

According to the research methodology, variations were carried out with air injection Q_{in} зand characteristic low (winter), high (summer) and medium (autumn and spring) temperatures T_{in}. The following values were chosen for temperature: 12,2 °C, 9,8 °C, 28,1 °C. Graphs of temperature distribution in the air duct of the heat exchanger for pumping Q_{in} = 500 m^3/hour shown in fig. 3. Analyzing fig. Figure 3 shows the tendency of the air temperature change along the entire length of the duct, characteristic of the results of numerical modeling. Therefore, let's proceed to the calculation of the experimental regression equations and their comparison with the theoretical ones.

After processing them in the Wolfram Cloud software package, a second-order regression equation was obtained, which shows the dependence of the change in air flow temperature ΔT_a in a U-shaped vertical soil heat exchanger from research factors in coded form:

$$\Delta T_{aU} = 2{,}61041 - 0{,}0768179\ X_1 + 7{,}00294\ X_1^2 - 2{,}63706\ X_2 + 0.520464\ X_1 X_2 + 0{,}111111\ X_2^2. \quad (1)$$

Statistical processing of equation (1) is given in Table 1.

Table 1

Results of statistical processing of equation (1)

Coefficient	Value	Deviation	Student's criterion	Probability
a_{00}	2,61041	0,164128	15,9047	0,000540439
a_{10}	– 0,0768179	0,0898966	– 0,854514	0,455629
a_{20}	– 2,63706	0,0898966	– 29,3344	0,0000870011
a_{12}	0,520464	0,1101	4,72718	0,0179381
a_{11}	7,00294	0,155705	44,9756	0,0000241974
a_{22}	0,111111	0,155705	0,713598	0,526981

Comparing the calculated Student's criterion with the table one $t_{0,05}(9)$ = 2,26 we will carry out deviations of insignificant regression coefficients. Let us present equation (1) in decoded form:

$$\Delta T_{aU} = 8{,}77254 - 0{,}00956083\ Q_{in} - 0{,}322949\ T_{in} + 0{,}0000790378\ Q_{in}\ T_{in} + 0{,}0145349\ T_{in}^2. \quad (2)$$

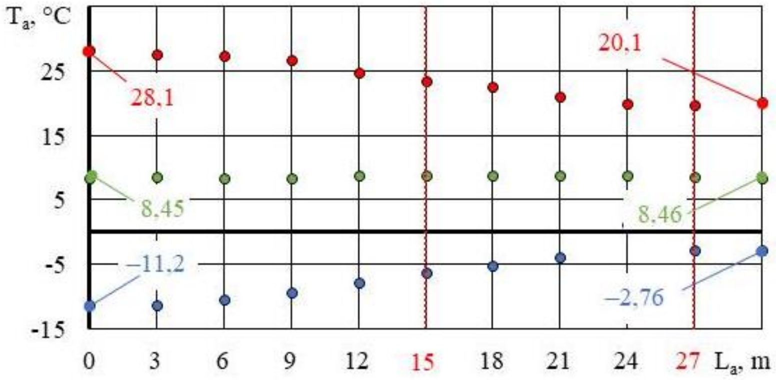


Fig. 4. Graph of the experimental dependence of the air flow temperature T_a from the path of its movement L_a for a U-shaped vertical soil heat exchanger with air injection of 500 m^3/h

The graphic interpretation of the theoretical dependence [17, 18] and the experimental one (1) is presented in fig. 5.

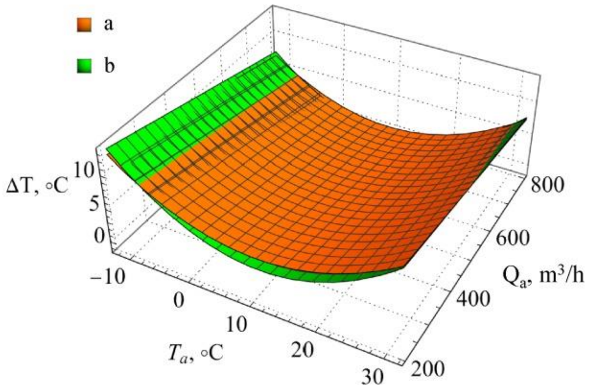


Fig. 5. Graphs of theoretical (a) and experimental (b) dependences of air flow temperature changes ΔT_a from research factors for U-shaped vertical soil heat exchanger

Visual analysis of fig. 5. indicates the identity of theoretical and experimental dependencies. The Pearson correlation coefficient is 0.94. Also, Fisher's criterion is $F = 2{,}02 < F_{\text{т}} = 2{,}49$. This confirms the adequacy of the obtained model. Therefore, theoretical dependencies can be used in further production calculations.

Due to the similarity of the theoretical and experimental regression equations of changes in air flow temperature ΔT_a in the U-shaped vertical soil heat exchanger, we will conduct a visual and statistical comparison of the calculated thermal efficiency (Fig. 6).

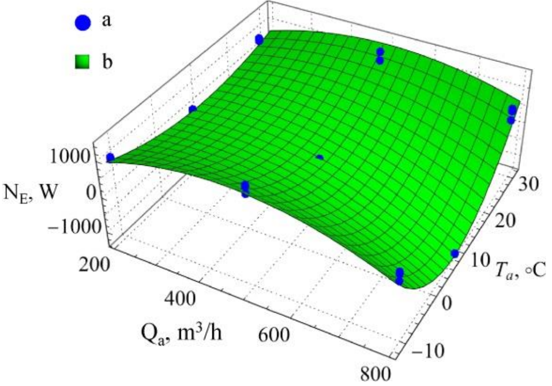


Fig. 6. Graph of experimental data (a) and theoretical dependence (b) changes in the effective heat capacity of the U-shaped vertical ground of the NE heat exchanger from research factors

Statistical comparison of experimental data with theoretical dependence according to the Pearson correlation coefficient - 0,95 and Fisher's test – $F = 1{,}93 < F_{\text{т}} = 2{,}98$ indicates the high adequacy of theoretical dependencies.

5. Conclusions

According to the results of experimental studies of the process of heating the air flow in a U-shaped vertical soil heat exchanger in production conditions, the dynamics of temperature changes throughout the year were established. The obtained regression equations of the second order of changes in air flow temperature ΔT_a and effective heat capacity N_E from temperature T_{in} and costs Q_{in} air flow at the entrance to the U-shaped vertical soil heat exchanger.

Statistical comparison of experimental data with theoretical dependence according to the Pearson correlation coefficient - 0,95 and Fisher's test – $F = 1{,}93 < F_{\text{т}} = 2{,}98$ indicates the high adequacy of theoretical dependencies.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ПРОЦЕСУ НАГРІВАННЯ ПОТОКУ ПОВІТРЯ У ВЕРТИКАЛЬНОМУ ҐРУНТОВОМУ ТЕПЛООБМІННИКУ

У статті розглядаються можливості використання ґрунту як джерела низькопотенційного тепла в Україні, де на глибині понад 10 метрів він зберігає сталу температуру +9…12 °С впродовж усього року. Це створює сприятливі умови для ефективного використання теплових насосів. Аналіз *технічних засобів вилучення теплової енергії з поверхневих шарів ґрунту демонструє, що вертикальні ґрунтові теплообмінники є найбільш ефективними для досягнення необхідних параметрів мікроклімату в тваринницьких приміщеннях.*

Дослідження процесу нагрівання потоку повітря у вертикальному ґрунтовому теплообміннику проведено у виробничих умовах на свинофермі ПСП «Агрофірма Нападівська» у Вінницькій області. Для підвищення ефективності системи нагнітання чистого повітря встановлено U-подібний вертикальний ґрунтовий теплообмінник, який підключено до вентиляційної системи приміщення для відгодівлі свиней.

Дослідження проводились на різних рівнях потоку повітря (200, 500, 800 м³/год) та температурі повітря в ґрунтовому теплообміннику, яка фіксувалась шість разів на день. Показники кліматичних умов визначались шляхом замірювання температури та вологості повітря, а також моніторингом динаміки температури впродовж року.

За результатами експериментальних досліджень процесу нагрівання потоку повітря в U- подібному вертикальному ґрунтовому теплообміннику у виробничих умовах встановлено динаміку зміни температур впродовж року. Отримані рівняння регресії другого порядку зміни температури повітряного потоку ΔT_a *і ефективної теплової потужності* N_E *від температури* T_{in} *і витрат* Q_{in} *потоку повітря на вході в U-подібний вертикальний ґрунтовий теплообмінник.*

Статистичне порівняння експериментальних даних із теоретичною залежністю за коефіцієнтом кореляції Пірсона – 0,95 і критерієм Фішера – $F = 1{,}93 < F_m = 2{,}98$ *свідчить про високу адекватність теоретичних залежностей.*

Ключові слова: *мікроклімат, температура, вологість, тваринництво, нагрівання повітря, ґрунтовий теплообмінник, теплообмін, потік повітря, теплопередача, енергоефективність, параметри теплообміну, температурний режим.*

Ф. 2. Рис. 6. Табл. 1. Літ. 18.

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