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Study of heat exchange processes in the cooling system of a poultry house with side ventilation

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Abstract. Modern systems for cooling the supply air in poultry houses are based on the use of spraying or evaporative systems. Both systems rely on the principle of adiabatic cooling, where water transitions from a liquid to a gaseous state through free evaporation, allowing for the reduction of the temperature of the external heated air in poultry premises. The objective of the research study was development of theoretical basis for using new method of cooling the outside air in poultry house ventilation systems is proposed, based on the use of water from underground wells and recuperative heat exchangers to cool the supply air. This method enables the reduction of the outside air temperature without increasing its relative humidity, unlike water spraying cooling systems, for example. Numerical modeling was conducted to obtain velocity fields, temperatures, and pressure differentials in the air environment of the poultry house. The results show that the air temperature exiting the heat exchangers at 20 °C is heated up to 26.6 °C inside the poultry house. Thus, the temperature of the supply air with this cooling system does not exceed permissible norms. The velocities and pressure differentials are sufficient to ensure that the air exiting the supply valves reaches the middle of the poultry house.

Key words: computational fluid dynamics (CFD), heat exchanger; lateral ventilation system, recuperation, thermal regime.

INTRODUCTION

The traditional cooling system used in poultry houses to maintain regulated indoor microclimate is direct evaporative cooling (DEC) (Hoff, 2018; Liang et al., 2020; Boltyanska et al., 2022). In these systems, 100% fresh outside air is drawn through evaporative cooling pads on the lateral walls to meet heat and air quality constraints

(Raza et al., 2020). Consequently, the air temperature is reduced while simultaneously increasing moisture content. Moreover, DEC elevates the humidity of the supply air, thereby reducing heat loss from the birds (Rozenboim et al., 2007). Apart from thermal stress, high humidity indoors leads to other adverse health consequences, as it increases the amount of ammonia emitted from poultry litter (Kristensen & Wathes, 2000). This results in decreased feed consumption and egg production by the birds, as well as increased mortality rates, leading to reduced productivity and profitability within the industry.

Modern cooling systems for supply air in poultry houses (Donald, 2012; Czarick & Fairchild, 2014) are based on the use of spraying or evaporative systems. Both systems rely on the principle of adiabatic cooling (Hui et al., 2018), where water transitions from a liquid to a gaseous state through free evaporation, allowing for the reduction of the temperature of the external heated air in poultry premises.

The second method involves spraying devices such as nozzles or disk sprayers, which produce an aerosol or spray containing small water droplets (Kim et al., 2008). Nozzles come in two types: low-pressure and high-pressure water systems. When using the nozzle method for air cooling, it is necessary to have a special water treatment system - purification, filtration, etc., as high salt content quickly impairs the operation of the nozzles. Additionally, operating such systems requires significant electricity consumption.

Drawbacks of the cassette method include high aerodynamic resistance and high installation costs. Additionally, a disadvantage of this method is the clogging of cassette channels with dust during operation. It should be noted that mold forms on the clogged surface of the cassette, introducing components into the supply air, which, in high humidity conditions, contributes to the onset of various diseases in poultry. In case of untimely cleaning of the cassettes, algae may grow on their surfaces. These factors prompt frequent replacement of cassettes as early as the first year of operation. The maximum service life of cassettes does not exceed 10 years and depends on water quality, preventive maintenance, and operational regime. The effectiveness of cassette cooling also largely depends on the airtightness of the poultry house.

In this research was used methods of computational fluid dynamics (CFD). It is a branch of fluid mechanics that uses numerical analysis and algorithms to solve and analyze problems involving fluid flows. CFD is widely used in various engineering fields to simulate the behavior of fluids (liquids and gases) in and around objects.

The main problem identified in this research is the inefficiency and associated issues with traditional and modern cooling systems in poultry houses. Specifically, traditional direct evaporative cooling (DEC) systems, while reducing air temperature, increase humidity levels, leading to thermal stress, adverse health effects, reduced feed consumption, lower egg production, and higher mortality rates among poultry. Modern cooling systems using spraying or evaporative methods also have significant drawbacks, such as high aerodynamic resistance, high installation and maintenance costs, clogging of channels, mold and algae growth, and substantial electricity consumption. These issues highlight the urgent need for a more effective, sustainable cooling system that can maintain an optimal microclimate in poultry houses without the negative impacts associated with increased humidity and high maintenance requirements.

Given these numerous challenges faced by the poultry industry, the ability to create a suitable and sustainable cooling system for poultry houses in Ukraine is a pressing necessity.

The purpose of the study was to develop a theoretical basis for use of a new method of cooling outside air in ventilation systems of poultry houses, based on use of water from underground wells and recuperative heat exchangers to cool the supply air.

MATERIALS AND METHODS

In poultry houses, a lateral cooling system is proposed for the summer period when the outside air temperature reaches 27 °C (Rozenboim et al., 2007). Heat exchangers are installed on the supply air valves on the exterior side of the poultry house. Groundwater is used as the coolant. Previous studies by the authors (Trokhaniak et al., 2023a), which focused on developing heat exchangers for such a cooling system, have provided detailed insights. The required water flow and all other parameters of the heat exchanger are presented in this article. Analyzing the results, it is projected that through these heat exchangers, the external warm air will pass and be cooled down to 20 °C. The poultry house contains 41,000 birds, each weighing 3 kg, of a meat breed kept on the floor. The poultry serves as a heat source, modeled as a first-kind boundary condition with a temperature of +41 °C. The bedding on the concrete floor was not accounted for in this model. Future research will include modeling the bedding as a porous zone, addressing gas emissions from it, and performing air composition analysis using species transport models.

Additionally, based on previous studies by the authors (Trokhaniak et al., 2023b, 2023c), exhaust fans, totaling 4 units for half of the poultry house, are installed on the lateral wall with a combined airflow rate of 42.8 kg s^{-1}. This airflow volume is sufficient for removing excess heat from the poultry house. Also considered are the supply air valves, positioned at a height of 0.21 m above the floor level. The spoiler angle over the valve is set at 73 degrees, with a spoiler length of 0.2 m. The nearby valves to the fans are closed, specifically: 9–10, 17–18, 25–26, and 33–34. Thus, 32 valves are utilized for half of the poultry house. The Air Inlet Valve 3000-VFG valves have a width of 0.86 m, and their opening height is 0.09 m.

The poultry house has dimensions of 120×21 meters and a height of 5.3 meters, the total volume of the poultry house is 5,234.4 m^3. To reduce the use of computational resources, a 'symmetry' boundary condition was applied. Consequently, the width of the poultry house is 10.5 meters. The floor is made of concrete 0.1 m thick, with polystyrene insulation 0.05 m thick above and below it. At positions 2 m from the walls, the thickness of the thermal insulation material is increased to 0.1 m. Assuming the temperature is 10 °C. The walls are constructed as three-layered, with concrete 0.06 m thick on both sides, and polystyrene insulation 0.1 m thick in between. For simplicity in the model, the ceiling is also constructed as three-layered, with concrete on both sides and Izovat 30 thermal insulation material 0.1 m thick in between. Boundary conditions of the third kind (Fig. 1) with a temperature of 40 °C and a heat transfer coefficient of 10 W $(m^2 K)^{-1}$ were applied to all exterior walls and the ceiling. Assuming low wind speeds were observed at the poultry house location.

The geometry of the poultry house was created in ANSYS Design Modeler 2023 R1, and boundary conditions were set. Then, the geometry was transferred to ANSYS Meshing 2023 R1 for mesh generation. Meshing was performed using the CutCell method. The minimum face size is 0.015 m, and the maximum face size is 0.12 m. For the supply air valves and exhaust fans, the mesh was refined with minimum element sizes of 0.01 m and 0.04 m, respectively. Mesh refinement was applied for more accurate results at the inlet and outlet of the poultry house. As a result, the orthogonal quality of the mesh is 0.214, with a total of 4,485,116 elements and 4,854,992 nodes.

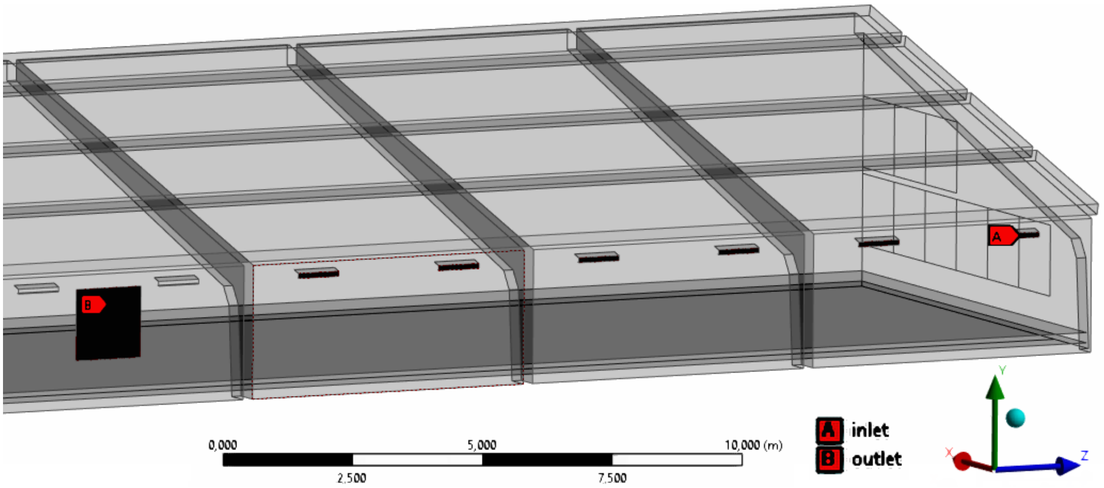

Figure 1. 3D model of the poultry house.

Numerical simulations were conducted directly in ANSYS Fluent 2023 R1. The model employed the Navier-Stokes equations (Trokhaniak & Klendii, 2018), the standard k-ε turbulence model, and the Discrete Ordinates radiation model (ANSYS). The methodology of mathematical modeling in the technical field of agriculture and in determining microclimate parameters is detailed in (Kaletnik et al., 2020; Kic, 2016). Certain aspects of this methodology can be applied in this study. The modeling was conducted as steady-state.

RESULTS AND DISCUSSION

Figs 2–3 depict the results of numerical modeling of the poultry house at four sections along the length of the building - 10.25 m, 43.25 m, 74.75 m, and 109.25 m along the *xy* axis. The first and second sections correspond to the midpoint of the 4th supply air valve and the 15th valve, respectively. The third section is located at the 3rd exhaust fan (between the 25th and 26th supply air valves). The fourth section is in the middle of the 37th supply air valve. Along the length of the poultry house, there are 40 supply air valves, out of which 32 are in use.

On sections 1, 2, and 4, flow lines in the poultry house are displayed (see Fig. 2, a; b; d). It is observed that the valves and spoilers are strategically positioned. The airflow exits the valves at a velocity of 14.36 m s^{-1}. Upon reaching nearly the middle of the poultry house, it descends, losing velocity, towards the birds. Between the swift airflow and the birds, a large vortex is formed, which provides fresh air delivery to the birds. In the upper part of the poultry house, along the centerline, a small air vortex is created due to the specific construction of the poultry house. Additionally, there is a separation of the airflow due to its intensive supply. This results in turbulence in the airflow and intense mixing of fresh air with exhaust air in these sections. At certain points, near the inlet of the supply air valves, the maximum airflow velocity reaches up to 14.62 m s^{-1}. The pressure at the inlet of the supply air valves reaches 124.3 Pa.

In turn, at the exhaust fans (see Fig. 2, c), the air velocity is 6.13 $m \cdot s^{-1}$. The air is uniformly removed from the poultry house. The pressure at the outlet is –3.31 Pa.

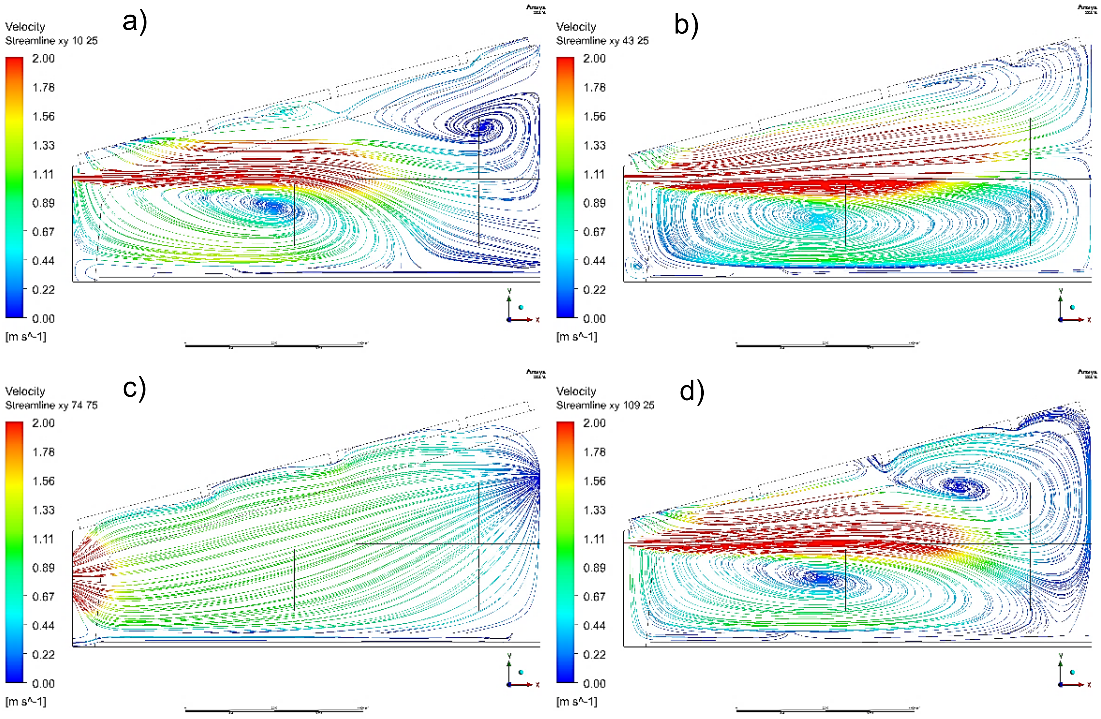

Figure 2. Flow lines ($m \cdot s^{-1}$) in the poultry house along the xy axis at distances from the front end wall: a – 10.25 m; b – 43.25 m; c – 74.75 m; d – 109.25 m.

In Fig. 3, the temperature distribution at various sections in the poultry house is presented. It can be observed that the cooled air from the heat exchangers at a temperature of 20 °C (Fig. 3, a, b, d) is directed from the valves into the poultry house. After traveling approximately 1.5 m, it heats up, and the cold airflow disperses throughout the space. The average temperature in these sections ranges from 24.44 to 26.11 °C.

Considering the large length of the poultry house, there is a temperature stagnation zone near the wall at 1.5 m (Fig. 3, b) and 0.5 m (Fig. 3, c), where temperatures range from 28 to 32 °C. The model assumes that the birds are not located within 0.5 m from the wall. Therefore, only a very small amount of birds will experience some discomfort (Fig. 3, b). Near the ceiling, at a short distance of about 0.1 m, temperatures range from 28 to 40 °C. These elevated temperatures are due to the high outside air temperature (40 °C) and the intensity of solar radiation. Fig. 3, c depicts the temperature field at the level of the 3rd exhaust fan. The temperature in this area is slightly higher, ranging from 26.82 to 27.35 °C. This is because there is no supply of cooled air in this area. The heated air enters the exhaust fan removal area, where the temperature at the outlet is 26.84 °C.

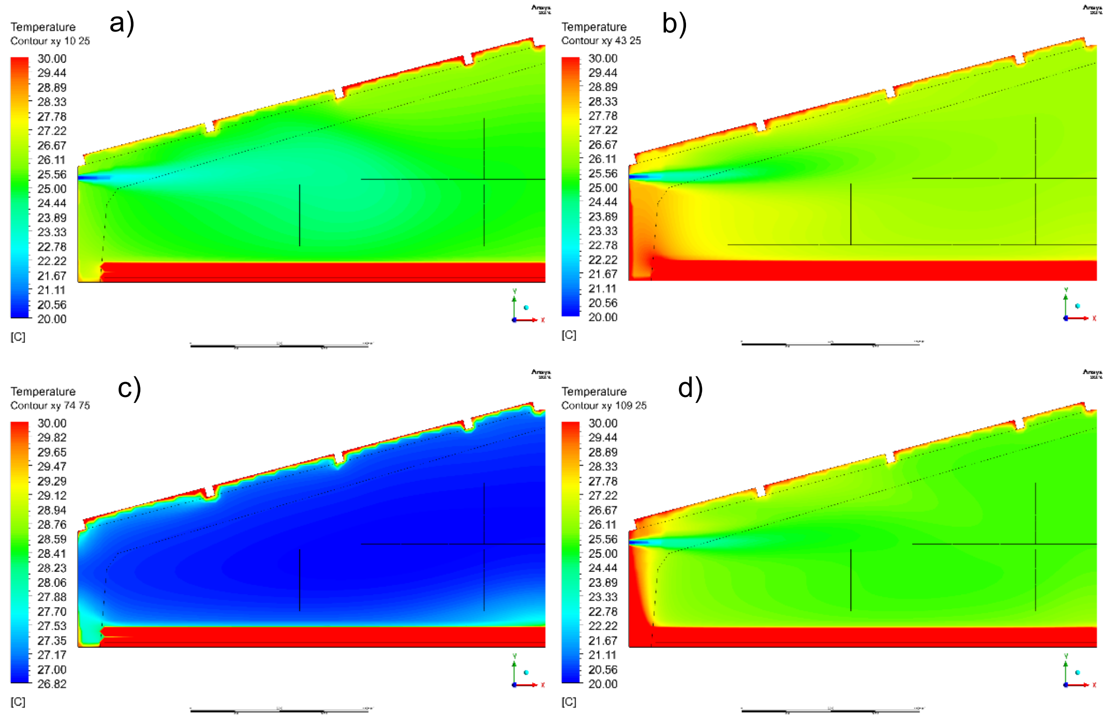

Figure 3. Temperature losses (°C) in the poultry house along the *xy* axis at distances from the front end wall: a – 10.25 m; b – 43.25 m; c – 74.75 m; d – 109.25 m.

In Fig. 4, the velocity field (Fig. 4, a) and the temperature field (Fig. 4, b) at a height of 0.7 m from the floor level are presented. These results are the most interesting and important since the birds are housed on the floor. Considering the technical standards for poultry management, the air velocity near the birds should not exceed 2 $m \cdot s^{-1}$. Therefore, the results in Fig. 4, a are shown within the range of 0–2 $m \cdot s^{-1}$. Considering the results presented in Figure 3 and the high air velocities at the inlet of the supply air valves, which reach 14.62 $m \cdot s^{-1}$, only in small areas does the air velocity exceed 2 $m \cdot s^{-1}$. The average air velocity in the section (see Fig. 4, a) is 0.74 $m \cdot s^{-1}$, and the pressure is 0.599 Pa. These results demonstrate the effectiveness of the ventilation system in the poultry house.

The air temperature near the birds during the hot period of the year should not exceed 28 °C. Considering the results of the numerical modeling (see Fig. 4, b), the air temperature exceeding 28 °C occupies an area of no more than 7.8%. This demonstrates sufficient efficiency of the poultry house cooling system. Slightly lower air temperatures are observed on the rear and frontal sides of the poultry house, starting from 24.68 °C. The average temperature across the entire area of the poultry house at a height of 0.7 m from the floor level is 26.55 °C.

On Fig. 5, the airflow velocity distribution within the 3D poultry house is depicted, ranging 0–2 $m \cdot s^{-1}$. As observed, the valves operate efficiently by delivering fresh, cooled air into the center of the poultry house. The two nearest valves to the fans are closed.

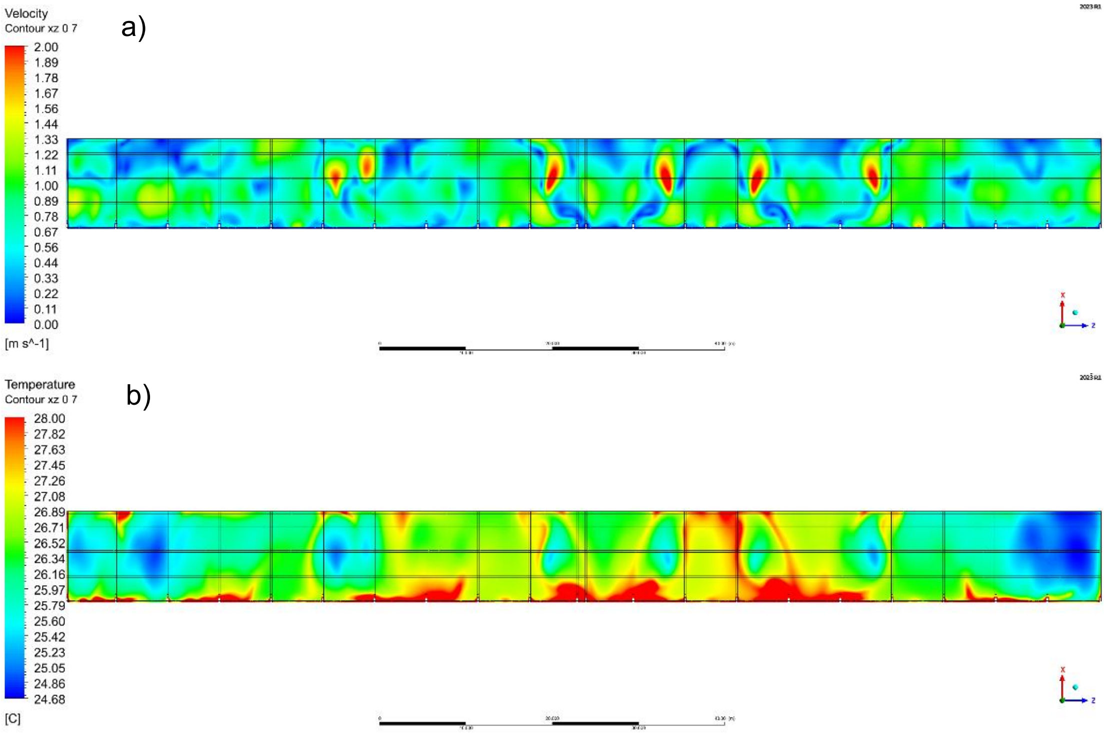

Figure 4. Velocity field, m·s^{-1} (a), and temperature field, °C (b), in the poultry house along the *zx* axis at a height of 0.7 m from the floor level.

However, there is a certain attenuation and downward airflow at valves 11, 16, 19, 24, 27, and 32 (see Fig. 5). This phenomenon is ultimately observable in Fig. 4, a as well. This phenomenon is not observed at valves 8 and 35 because there are no fans directing airflow towards the frontal and rear walls from these valves. The airflow exiting from valves 1–8 and 35–40 exhibits a more uniform airflow pattern.

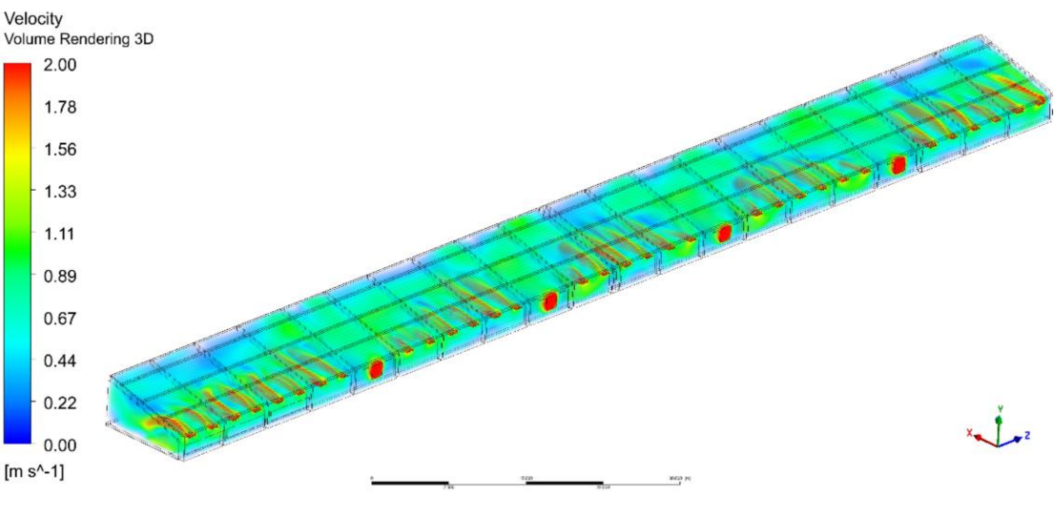

Figure 5. Visualization of the volumetric airflow distribution in the poultry house ranging from 0 to 2 m·s^{-1}.

In Fig. 6, b, the temperature distribution along the *zy* axis at a distance of 5.25 m from the side wall is depicted. As a result of numerical modeling, several elevated temperatures exceeding 28 °C were identified near the third exhaust fan and the ceiling. However, such stagnant temperature zones are insignificant and do not significantly affect the main flock of birds.

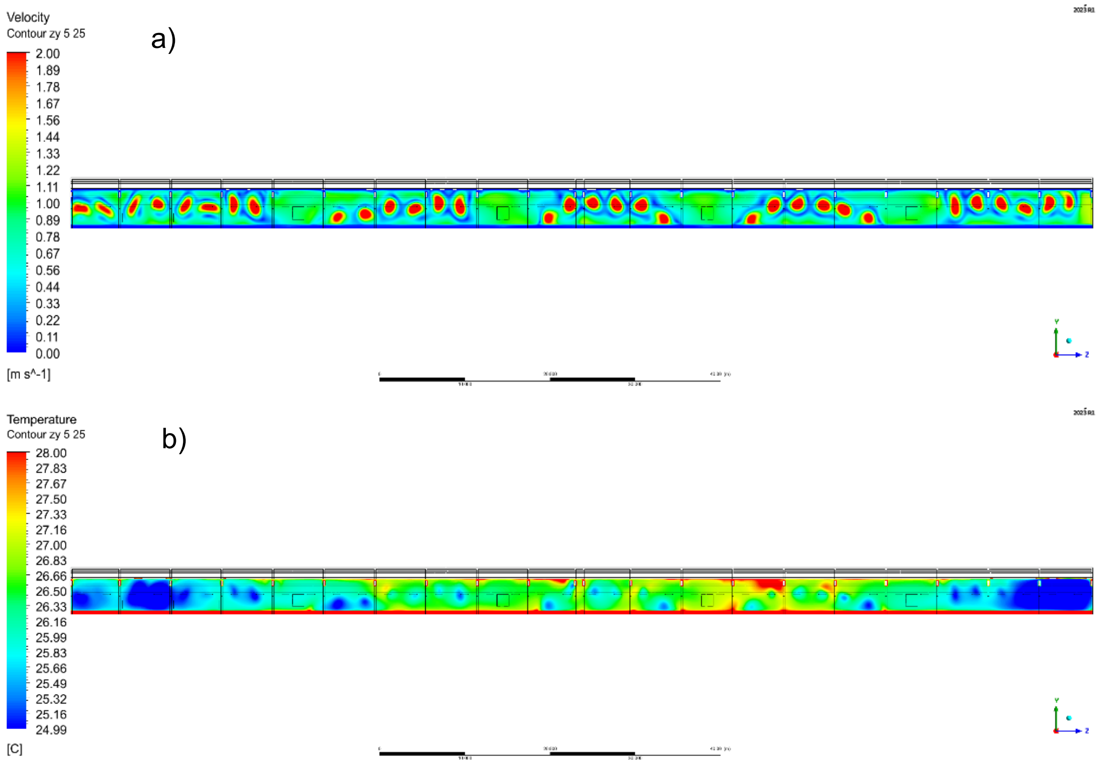

Figure 6. Velocity field, m·s^{-1} (a), and temperature field, °C (b), in the poultry house along the *zy* axis at 5.25 m from the side wall.

The modeling of the air environment in the poultry house demonstrated the efficiency of the proposed cooling system. The research results show a more stable relative humidity compared to those proposed by other authors (Donald, 2012; Czarick & Fairchild, 2014), which are based on spraying or adiabatic cooling (Hui et al., 2018). Cooling systems from different authors are accompanied by a significant increase in humidity, which ultimately leads to poultry diseases, mortality, and decreased production output in poultry farms (Ishchenko et al., 2019).

The use of evaporative cooling pads (Hoff, 2018; Liang et al., 2020; Boltyanska et al., 2022) also increases humidity in poultry houses. Additionally, it requires extra water treatment and excessive water consumption to maintain the microclimate in proper conditions.

All the above-mentioned cooling systems share common drawbacks: increased humidity in the poultry house, high water usage, and ultimately, reduced productivity of poultry farms (Wang et al., 2019). However, all these cooling methods perform their function despite these significant negative aspects. In the proposed cooling system, poultry will be in comfortable conditions, as much as possible.

The article is theoretical in nature; however, the authors conducted preliminary experimental investigations to validate the obtained results. Based on these preliminary studies, it can be stated that the proposed model is expected to have deviations of up to 12% from real data (Trokhaniak et al., 2019).

The research conducted in the poultry building is intricately linked to animal welfare. The primary motivation behind this research, as presented in the article, is to analyze energy inputs and the changes in microclimatic conditions within the building, with a significant focus on air flow dynamics. However, the underlying and critical objective of these analyses is to improve the welfare of the birds housed in these facilities.

The proposed system for cooling outside air in ventilation systems of poultry houses affects the health of birds as it provides: temperature regulation; humidity control and air quality improvement.

The results of this research have the potential to bring about significant improvements in poultry welfare. By addressing both the microclimatic conditions and energy efficiency, the study offers practical solutions that can be implemented to create a more sustainable and humane environment for poultry. This not only benefits the birds but also enhances productivity and profitability for poultry farmers, aligning economic and welfare goals.

CONCLUSIONS

1. The numerical modeling results investigated the cooling system during the hot period of the year with an outside air temperature of 30 °C in a 3D model of half of the poultry house. A new cooling system for poultry houses was proposed using heat exchange equipment, which would output air at a temperature of 20 °C. Groundwater is suggested as the cooling medium.

2. Velocity fields were obtained at various locations within the room along the xy- axis. The effectiveness of the placement of supply vents and spoilers above them was demonstrated. Fresh air flow exiting the vents at a speed of 14.36 m s^{-1} reached the center of the room, ensuring its quality. The temperature in these areas averaged between 24.44 and 27.35 °C, not exceeding the limit of 28 °C during the hot period of the year. Analyzing the results of the numerical modeling at a height of 0.7 m from the floor level, it was concluded that discomfort would be experienced by no more than 7.8% of the birds with the proposed cooling system. The average velocity was 0.74 m s^{-1}, with an air temperature of 26.56 °C. Only in certain areas did the temperature exceed 28 °C.

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