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ANALYSIS OF THE AIR EXCHANGE IN LIVESTOCK BUILDING THROUGH THE COMPUTATIONAL FLUID DYNAMICS

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Abstract

Increasing consumption of meat and meat products worldwide is closely linked to improving the living environment for livestock. According to zoo experts, the appropriate microclimate in buildings leads to improved metabolic processes in their cultivation and contributes to their rapid weight gain. The issue of raising new-borns and young animals is especially relevant. Achieving optimal parameters of the microclimate in the premises, together with the necessary veterinary care for new-borns reduces stress and mortality in them. The above requires the implementation of new and modern engineering solutions in the design and construction of livestock buildings. The use of numerical simulations, through CFD programs for modelling and solving engineering problems, as well as the creation of adequate mathematical models, is a prerequisite for reducing the time and resources to solve a problem. Based on the accumulated experience of the authors on the microclimate in livestock farms in this publication, a numerical simulation of air exchange in a livestock building for breeding sows with young piglets is presented. The physical model, research and analysis are realized in the middle of Ansys Fluent. Two models of air exchange organization in the livestock building are proposed. The obtained data on the temperature and speed fields in the building will lead to an improvement of the microclimate in the considered site. In addition, they could serve as a basis for conducting the next series of computer simulations. The built models can be adapted for other building constructions for breeding other types of animals. The analysis of the data and a more in-depth examination of the factors related to animal husbandry could help to increase pork yields on livestock farms.

Keywords: Livestock farm, fluid dynamics, CFD model, organization of air exchange, mathematical model.

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1. Introduction

In industrial pig farming, the main goal is to achieve the lowest possible price per kilogram and high quality meat. Apart from quality fodder, the other main factor is the provision of an optimal microclimate in the livestock building. Young piglets are very sensitive to ambient temperature and air mobility. Due to their high metabolic activity, sows are highly susceptible to heat stress. From all the factors listed so far, it follows that the temperature in the pig holdings must not exceed 26 °C [1–3].

Computational fluid dynamics (CFD) is a powerful tool for analysing systems composed of material flows, heat transfer, as well as various chemical processes based on computer simulations. It is widespread in many industrial and non-industrial spheres. Some of the many examples of applications are in the aviation and automotive industries, hydrodynamics of ships, hydraulic machines, air exchange in buildings, including livestock [4–6], chemical and combustion processes, etc. The advantages of design using the CFD to methods based on experiments:

– significantly reduced time and resources for development;

– ability to study systems in which conducting controlled experiments is impossible (such as very large or very small systems);

– ability to explore systems in potential danger (for example, for safety studies or various disaster scenarios);

– almost unlimited level of detail of the results obtained;

– opportunity to explore restricted systems.

The numerous advantages of CFD modelling are the clear explanation for its wider recent use [7–9].

2. Materials and methods

The computer simulation is based on a mathematical model, through which it is possible to control the parameters of the system. The simulation object model is universal enough to describe objects that are close to the target and at the same time simple enough to provide the necessary research. To achieve the main goal of the study – analysis and comparison of the organization of air exchange in a livestock building for breeding sows with young piglets, the data from experimental studies of the physical model of the building were used [10].

Two types of numerical experiments were performed, one identical to the physical model [11, 12] (for its validation) and the second different from the first. The quality of air exchange in this case is described by the lack of congestion zones and zones with higher air velocities in the animal zone, as well as the uniformity of the velocity field [13]. The other parameter that is the subject of the study is the air temperature in the considered area.

The model is made of a solid material that corresponds to the one used to make the physical model discussed above, with the following warm physical characteristics: Exterior walls of the building with 3.33 W/m^2 heat flow; wall thickness – 0.03 m; material density ρ–35 kg/m^3, specific heat Cp – 1500 J/kg.K, thermal conductivity 0,033 W/mK.

In the implementation of the model are included heat inputs from external influences. Heat transfer through solid building structures and sunlit elements. Heat transfer and solar radiation through glazed elements. The area of the glazed elements is in accordance with the veterinary requirements. The heat of moisture (wet floor) is also included. Also it is included the heat released from animals as well as the heat flow caused by the released water vapor from the animals. Heat flows from radiant or other heating of young animals, imposed by climatic conditions are taken under consideration as well. The heat inputs of the artificial and night-time lighting are ignored which is motivated by the type of lighting fixtures [10].

Geometry of the model defines the objects and regions in which the research will be conducted. Depending on the desired accuracy, the geometric model can be simplified by removing some of the elements in the existing physical model or some geometric shapes are simplified by being represented as simpler geometric shapes. For example, elements that do not affect the research process can be removed. Another example is the placement of planes of symmetry. The geometric model is based on the actual dimensions of the model, the particularities when it is created are mainly related to the setting of the geometric parameters of the building and the air distribution system and also the dimensions and positioning of the inlet and compensation holes. **Fig. 1, 2** are presented the geometric parameters of the modeled building.

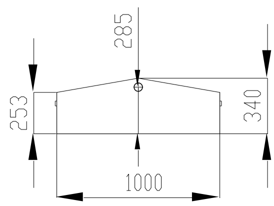

Fig. 1. Model dimensions

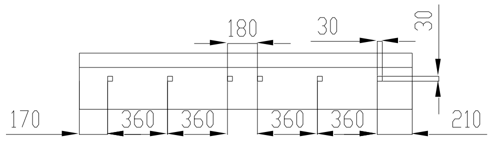

Fig. 2. Location of the compensation holes of the model

Fig. 3, 4 are shown the two main elements of the model being implemented – Livestock building with compensating holes and air distribution pipeline. Once the boundaries of the object under investigation have been recreated, it is necessary to create a computational mesh. The created mesh is tetra hybrid and contains 838,805 cells, 1,706,211 faces and 158 127 nodes. The computational network of the two sites is shown in **Fig. 5, 6.**

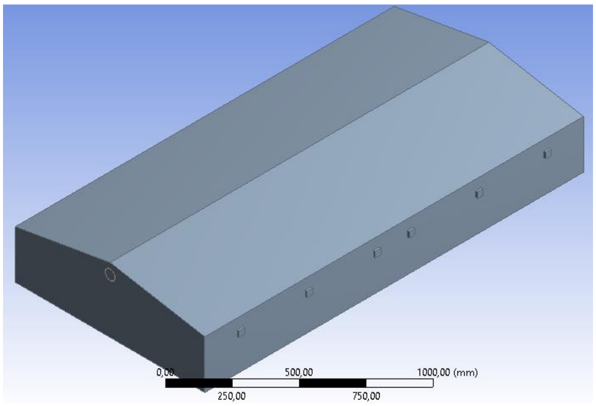

Fig. 3. Model of livestock building

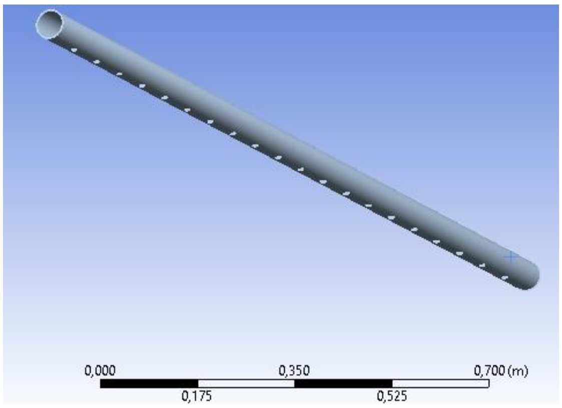

Fig. 4. Air distribution pipeline model

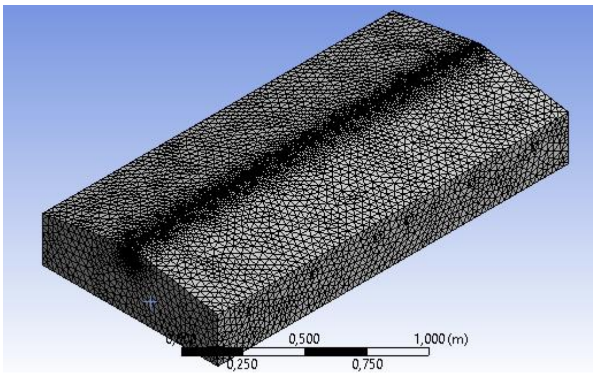

Fig. 5. General appearance of the mesh, created to perform the calculations

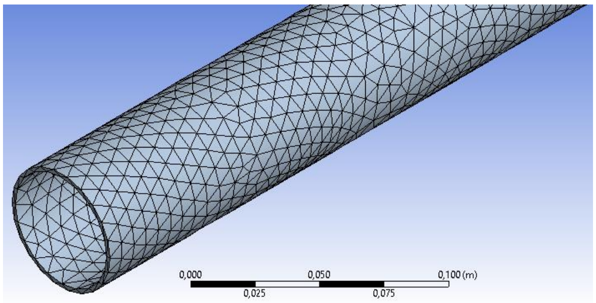

Fig. 6. Mesh of the air distribution pipeline

In the numerical simulation are set boundary conditions identical to those in the experimental study [14]:

– inlet of the air distribution pipeline – mass flow 0.004 kg/s with temperature 293,15 K;

– piecewise – linear set up for density in the range of 273.15 K to 313.15 K, analogy is the setting of the other air parameters – specific heat и thermal conductivity;

– exterior walls of the building with a heat input of 3.33 W/m^2, wall thickness 0.03 m, density ρ – 35 kg/m^3, specific heat *Cp* – 1500 J/kgK, thermal conductivity 0.033 W/mK.

The amount of chilled air is equal to that of the physical model and is consistent with the cooling load of the object and the temperature mode of the absorption refrigeration machine.

Setting up a mathematical model is related to the knowledge of the causal relationship arising from the laws of energy storage, the mass, the amount of movement, and so on. It is preceded by the formalization of the actual process and drawing up a scheme in which negligible factors are ignored, certain conditions are idealized. The boundary conditions in compiling the model are presented in **Table 1**. The number of differential equations in mathematical modeling depends on the type of processes that need to be studied and analyzed, and they can differ from one another with some specific features.

Table 1
Boundary conditions

	Boundaries	Boundary conditions
A blue color face	inlet	Mass flow inlet – 0.004 kg/s
A red color face	outflow	flow rate weighting – 1
External walls of the object	Heat flux	3.33 W/m^2

The amount of chilled air is equal to that of the physical model and is consistent with the cooling load of the object and the temperature mode of the absorption refrigeration machine.

Setting up a mathematical model is related to the knowledge of the causal relationship arising from the laws of energy storage, the mass, the amount of movement, and so on. It is preceded by the formalization of the actual process and drawing up a scheme in which negligible factors are ignored, certain conditions are idealized. The number of differential equations in mathematical modeling depends on the type of processes that need to be studied and analyzed, and they can differ from one another with some specific features. To solve the set task it is necessary to set the equation for continuity (1), as well as the equations for movement for established flow (2)–(4), according to [11].

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left[(\mu+\mu_T)\frac{\partial u}{\partial x}\right]+$$
$$+\frac{\partial}{\partial y}\left[(\mu+\mu_T)\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[(\mu+\mu_T)\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right], \tag{2}$$

$$\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}+\rho w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[(\mu+\mu_T)\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial x}\right)\right]+$$
$$+2\frac{\partial}{\partial y}\left[(\mu+\mu_T)\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial z}\left[(\mu+\mu_T)\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial x}\right)\right], \quad (3)$$

$$\rho u\frac{\partial w}{\partial x}+\rho v\frac{\partial w}{\partial y}+\rho w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[(\mu+\mu_T)\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]+$$
$$+\frac{\partial}{\partial y}\left[(\mu+\mu_T)\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+2\frac{\partial}{\partial z}\left[(\mu+\mu_T)\frac{\partial w}{\partial z}\right]. \quad (4)$$

To achieve the most accurate results in the solution of the current task, the most appropriate use of a standard k–ε model of turbulence [14–18]. This is a semi-empirical model based on the transport equations for turbulent kinetic energy (k) and the dissipation rate (ε) [19, 20]. They are defined by the following transport equations:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k, \quad (5)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+G_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-G_{2\varepsilon\rho}\frac{\varepsilon^2}{k}+S_\varepsilon, \quad (6)$$

where G_k – the generation of turbulence kinetic energy due to the mean velocity gradients; G_b – the generation of turbulence kinetic energy due to buoyancy; Y_M – the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate.

To solve the task it is also necessary to calculate the energy equation, which for the working environment of FLUENT has the following form:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\left(\vec{v}(\rho E+p)\right)=\nabla\left(k_{eff}\nabla T-\sum{}_j h_j\vec{j}_j+\left(\bar{\bar{\tau}}_{eff}.\vec{v}\right)\right)+S_h, \quad (7)$$

where k_{eff} – the effective conductivity (k+kt), where kt – the turbulent thermal conductivity, defined according to the turbulence model being used); $\vec{J}_j$ – the diffusion flux of species J; S_h – includes the heat of chemical reaction, and any other volumetric heat sources you have defined.

For all types of flows, FLUENT also solves the continuity equation and the moment of motion quantity.

3. Results and discussion

The distribution of velocities in the first series of experiments with uniformly located air duct openings is shown in **Fig. 7**. In the performed numerical experiments, zones with higher air velocity than the admissible values are observed. This is clearly seen in **Fig. 8**.

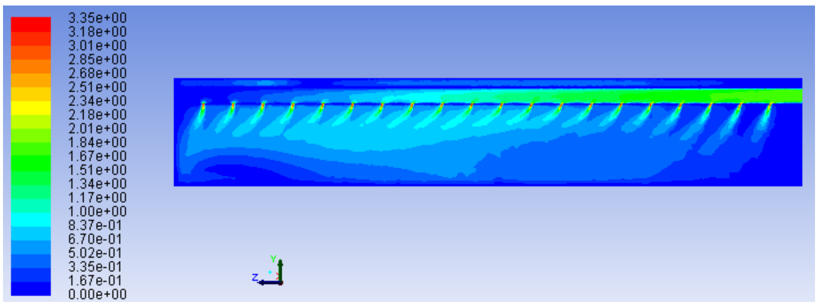

Fig. 7. Air velocity at cross section along the pipeline axis

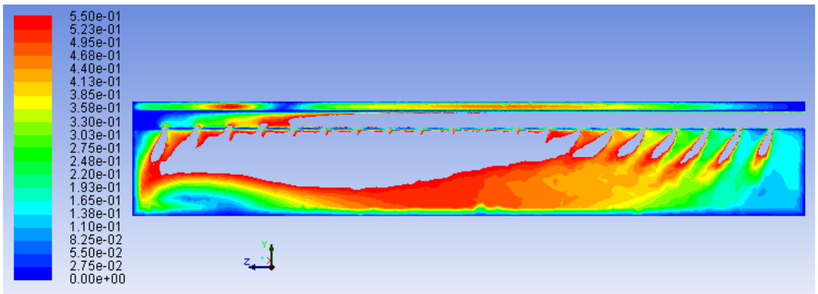

Fig. 8. Air velocity within the limit

Fig. 9 shows the distribution of air velocity in the animal habitat. **Fig. 10** shows the temperature distribution in the livestock building.

In **Fig. 11** are depicted areas with an air temperature higher than the normative requirement from which it can be seen that it has exceeded this temperature only at thermal bridges near the walls of the building.

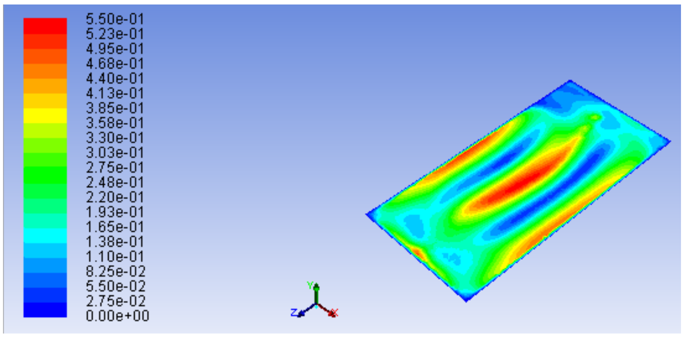

Fig. 9. Air velocity. Section above the level of animals

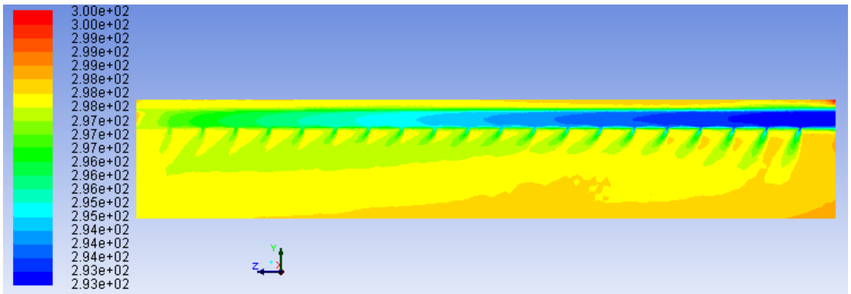

Fig. 10. Air temperature at section along the pipe axis

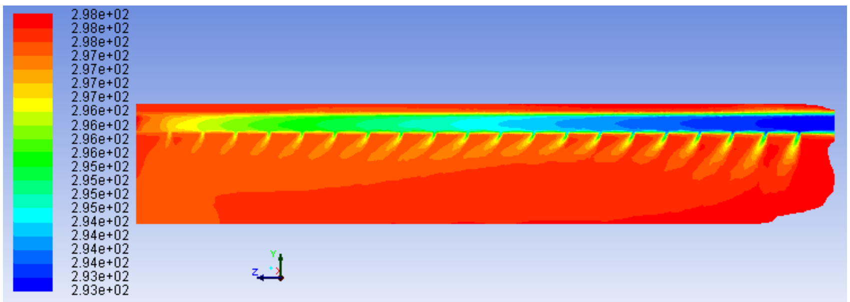

Fig. 11. Air temperature within the limit values

In a previous study [14], the authors developed a physical model of the building for raising sows with young piglets and conducted physical experiments. A comparison was made between the results of the experiment and the computer simulation to confirm the model. After processing the **Fig. 12–14** are presented in graphical form, respectively the results in sections Y3, Y4 and Y5. The results in sections Y1 and Y2 are omitted because they are close to the model walls and include thermal bridges, restricted areas and are outside the animal habitat.

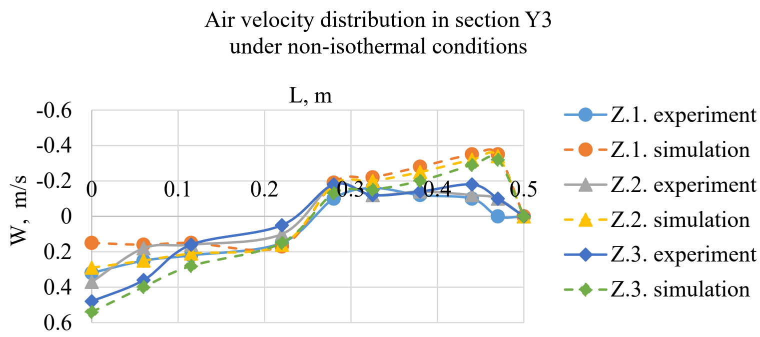

Fig. 12. Air velocity distribution in section Y3 under non-isothermal conditions

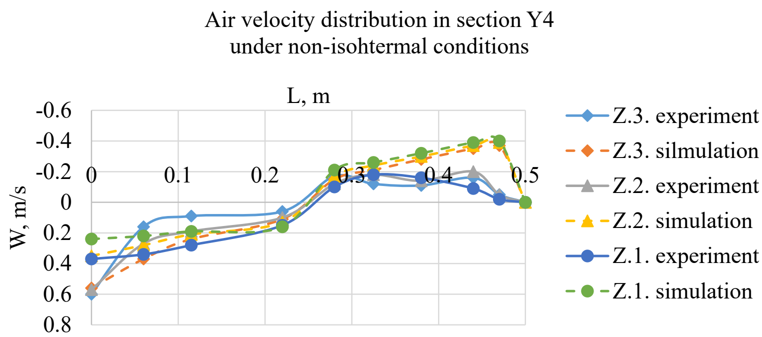

Fig. 13. Air velocity distribution in section Y4 under non-isothermal conditions

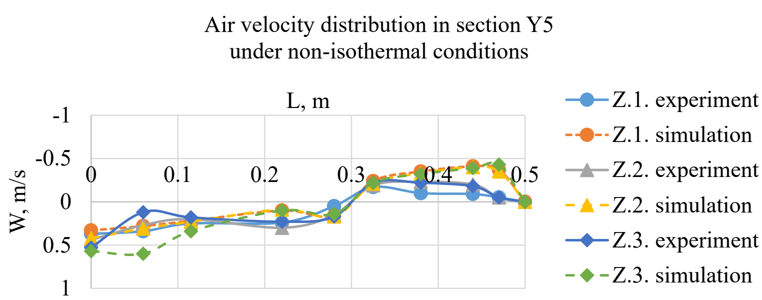

Fig. 14. Air velocity distribution in section Y5 under non-isothermal conditions

A comparison of the results obtained from the physical experiment and the computer simulation for the distribution of the air temperature was made. After processing, the results are presented graphically.

It becomes clear by **Fig. 12–17** that an error exists between the results obtained by numerical simulation and the experiment. This is due to the accumulation of measurement errors (thermometer accuracy and thermoanemometer accuracy). Another reason for the error is the idealization of the system in numerical simulation – however, the same coefficient of heat transfer between the ambient air and the outer surface of the physical model cannot be guaranteed.

From the results it can be judged that the results obtained from the simulation for the selected operating modes of the air distribution system can be assumed to be reliable. Both in the experimental results and the results of the computer model, there is a reduction of the speed by moving away from the leakage point, also increasing the uniformity of the speed field by approaching the floor as well as raising the temperature of the air by approaching the outer walls.

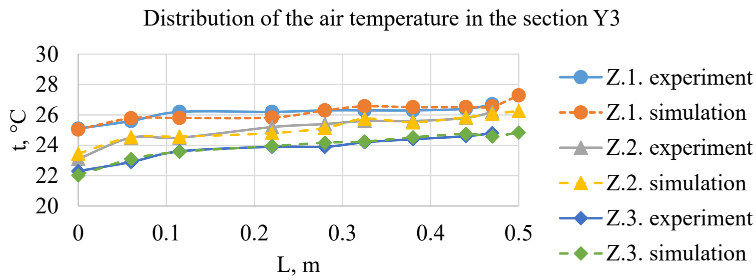

Fig. 15. Distribution of the air temperature in the section Y3

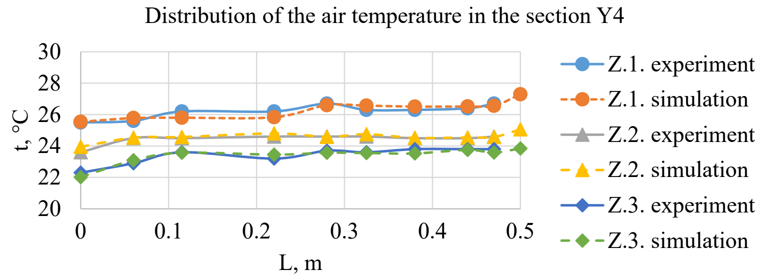

Fig. 16. Distribution of the air temperature in the section Y4

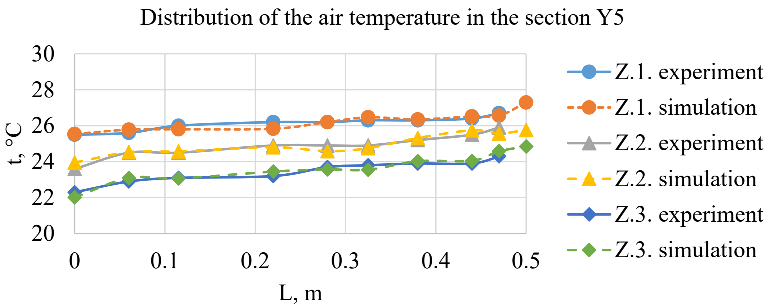

Fig. 17. Distribution of the air temperature in the section Y5

Good matching between the results of the experiment and the simulation give grounds for conducting simulations of different design of the air duct in order to optimize the speed and temperature fields in the studied building.

A numerical simulation was carried out using a two-row open duct while maintaining the mass flow rate with the first simulations. The geometry of this air duct is given in **Fig. 18**.

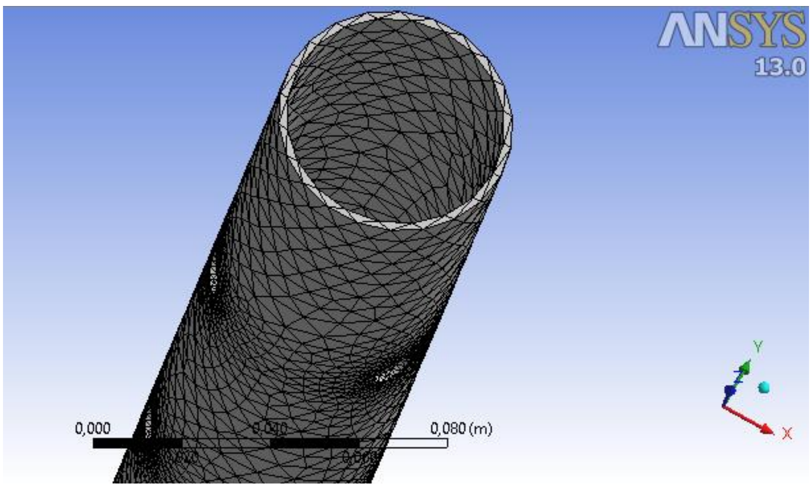

Fig. 18. Air distributor with two drain holes

The velocity fields of Simulation B with a 2-hole channel are shown in **Fig. 19** and **Fig. 20**. Accordingly in **Fig. 19** shows the leakage of air from the duct with two openings, and in **Fig. 20** speed profiles above where the animals are.

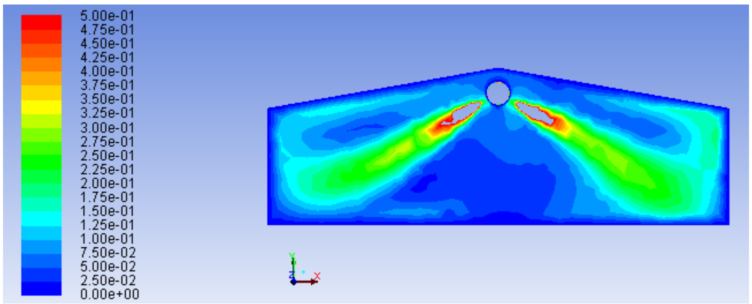

Fig. 19. Air velocity in 2-hole air distributor

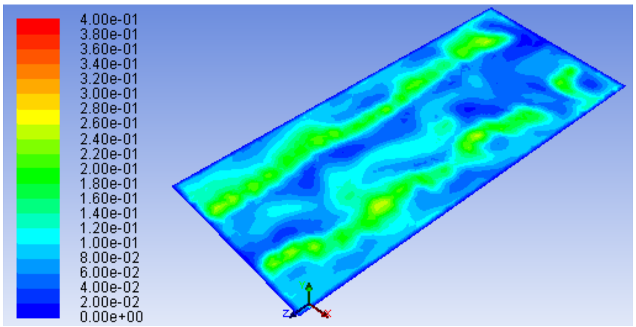

Fig. 20. Air velocity in a 2-hole air distributor in cross-section above the place where the animals are located

Comparison of the results obtained from a computer simulation for the two types of air distribution systems are shown graphically in the **Fig. 21–23.** The difference between the two cases is the design of the air distribution pipeline. Simulation A has two rows of holes longitudinally spaced along the pipeline at 30 ° to the axis of the pipeline. Simulation B is a single row of openings located below the axis of the pipeline.

Comparison of the results of air temperature distribution from the computer simulations are given in **Fig. 24–26**.

The results in **Fig. 21–23** show the greater uniformity of the speed field in the two-hole version. The velocity profile shows the even distribution of velocity and its distribution by layers, the layers close to the outer walls of the model are very slow and in the boundary layer the speed is almost 0. The low speeds along the exterior walls of the model explain the temperature distribution shown in **Fig. 24–26** form a higher temperature zone around the walls.

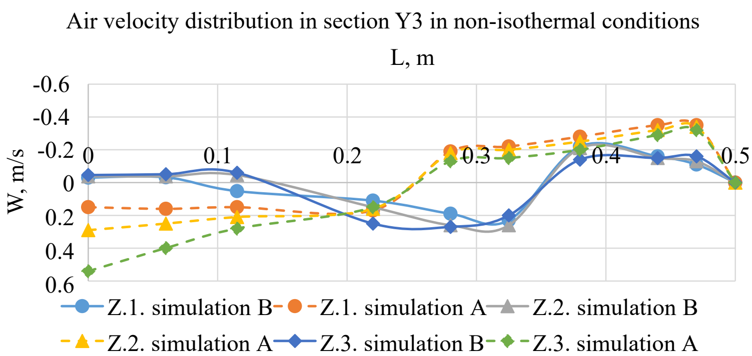

Fig. 21. Air velocity distribution in section Y3 in non-isothermal conditions

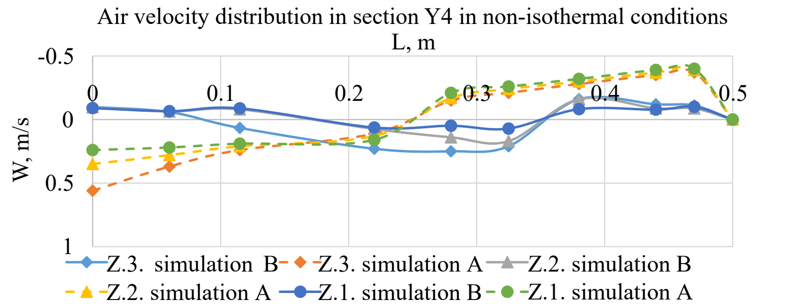

Fig. 22. Air velocity distribution in section Y4 in non-isothermal conditions

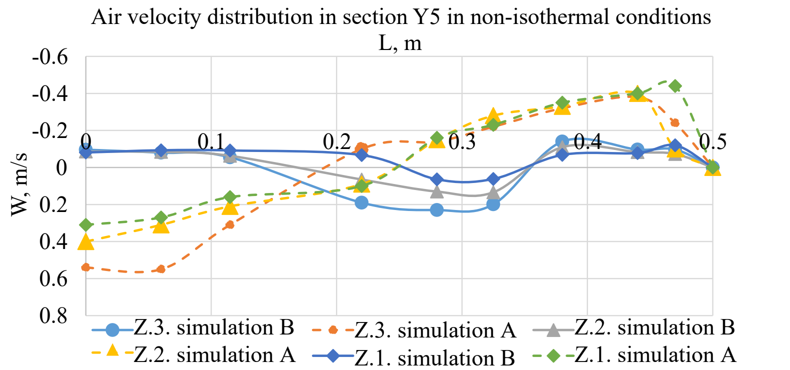

Fig. 23. Air velocity distribution in section Y5 in non-isothermal conditions

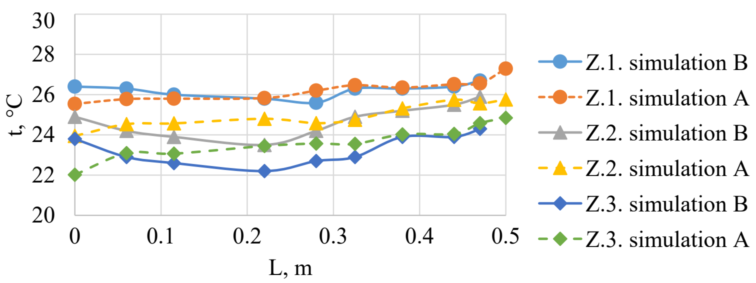

Fig. 24. Distribution of the air temperature in section Y5

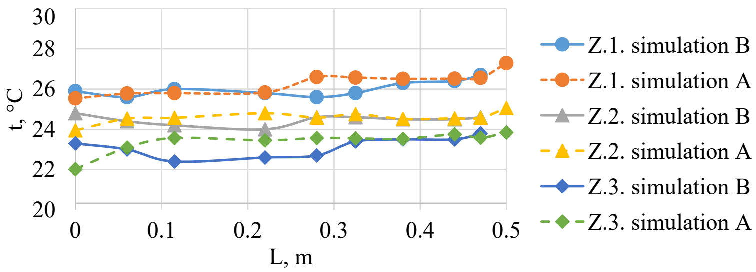

Fig. 25. Distribution of the air temperature in section Y4

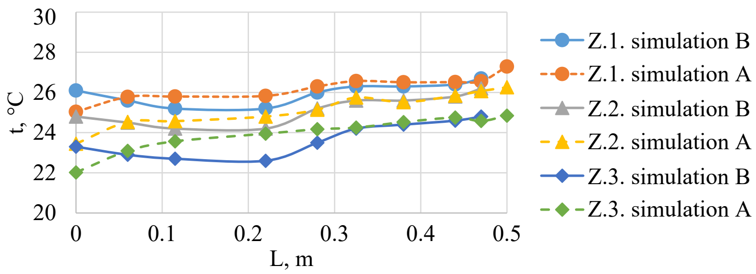

Fig. 26. Distribution of the air temperature in section Y3

The results of the simulation with respect to the selected operating modes of the air distribution system in the pig farm can be considered authoritative and reliable. When creating the model, the limitations that are imposed are the values of the speed of air movement and its temperature in the area of the animals. The created model can serve as a basis for conducting the next series of computer simulations on air exchange in other types of buildings for raising different animals. Conducting this type of research and implementing their results will improve the living environment of animals.

4. Conclusions

A numerical solution of the air exchange processes in a livestock building has been made with the help of two air flow distribution schemes. The study was conducted in stationary mode of operation of the physical model. The obtained results show that the air velocity does not exceed 0.4 m/s above the lying place of the animals and the air temperature is in the optimal range of 25÷26 °C. There is a decrease in velocity as you move away from the point of leakage, an increase in the uniformity of the velocity field as you approach the floor, as well as an increase in air temperature as you approach the outer walls. The results clearly show the greater uniformity of the velocity field in the two-hole variant. The velocity profile shows the uniform speed distribution and its distribution in layers, as the layers that are close to the outer walls of the model have a very low speed, and in the boundary layer the speed is almost zero. The nature of the air flow approaching the wall differs from the axis of symmetry of the flow. This leads to the appearance of tangential zones of velocity. The areas near the walls, as well as the corners of the buildings are separated as such without intensive air exchange (congestion zones), which explains the presence of higher temperatures in them, representing approximately 6 % of the cooling volume.

Acknowledgements

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