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The thermal model of winter aggregation of bees

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Abstract. For successful competition of the Russian beekeepers in the world honey market it is necessary to concentrate their attention on production of separate grades of this product. The most expensive honey is produced in spring and therefore it is necessary that the bees were successful in winter. The use of electric heating of bee hives does not always have a positive effect on the safety of bees in winter. In this regard, it is necessary to study more carefully the complex biological formation - winter bee hives. There were the basic equations for determining the physical parameters of the bee family in winter, including the energy characteristic. The established equations were included in the mathematical models describing the parameters of the microclimate. Mathematical processing of the obtained thermophysical model was carried out in the Comsol software product, which confirmed the validity of the use of the main functional dependencies and allowed to see the critical zones of the hive in temperature and humidity. Despite the large temperature changes outside the hive, it is maintained a fairly stable positive temperature at the level of +25ºC to + 32ºC inside. Such temperatures are not dangerous for bees. The images of temperature fields obtained in the course of mathematical processing confirm the assumptions that the lowest temperatures are in the lower part of the hive, and the higher ones are in the upper part. The results of the simulation will be used to determine the optimal power supply to electric heaters and to the place of their installation.

1. Introduction

Russia is one of the top ten honey producers in the world. Today, the market has a significant number of private companies engaged in wholesale purchases, processing, packaging and trade in honey. Russian honey producers are in difficult situation linked with a significant volume of honey imports at dumping prices, but of questionable quality of this product. In Russia, the honey export is not developed for many reasons of an objective and subjective nature. Exports can be significantly increased by obtaining elite Russian honey: white, chestnut, acacia, etc. However, it is necessary to bring the bee family to the honey yield with a certain level of development to get the maximum amount of honey. The level of honey productivity of a bee family strongly depends on the quality of wintering. It is especially important to pass a successful winter in the North Caucasus region, as there is a mild winter, but with sharp periods of cold temperature falls.

In winter, bees form hives and are in a passive state with slow life processes: metabolism can decrease in 100 times compared to its active state. Complex thermophysical processes take place in the hive: changes in humidity, movements of air masses, absorption of moisture, release and loss of heat, change in geometry and movement of the winter club in the volume of its dwelling. Without careful studies of the winter state of the bee family, the use of heating can lead to negative results:

overexpenditure of feed, early laying of eggs and mass death of bees, premature clogging of the bee's intestines, its disease with the subsequent death of the whole family. In this regard, a problem happened – on the one hand, electric heating should help bees to endure cold periods with minimal losses, but on the other hand, the lack of sufficient knowledge on the condition of bees under different ambient conditions. And the distribution of temperature fields inside the hive does not allow to recommend the necessary regime of work of heaters and the place of their installation.

Many researchers in Russia and abroad are engaged in mathematical descriptions of the processes taking place in the hive: Toboyev V. A., Tolstov M. S., Eskov E. K., Rybochkin A. F., Sukhodolets L. G., etc. [1-7]. Until 2000, researchers tried to describe more mathematically the basic physical processes that occur in winter in the hive. At the same time, in order to obtain solutions for these models, many assumptions and limitations have to be made, which lead to inadequate solutions. In recent years, there have been many software products that allow you to get results that are more precise and take into account a greater number of factors. In publications Toboeva V. A. analyzed the convective heat transfers using modern software products [3, 4]. In these works, there was a mathematical model of convective heat transfer in a cluster of bees saturated with a respiratory-gas mixture in the presence of internal heat generation. Influence of thermophysical parameters, factors of heterogeneity of accumulation on density of bees on heat transfer modes is established. Modeling of convective heat transfer of bees was carried out in the COMSOL 3.5 and accumulation of bees is presented as a porous medium. However, there are drawbacks in proposed models: no attention is paid to the specific period of the year (beginning of winter, end of winter, spring) and the presence of brood; there are no characteristics associated with the relevant feedstocks; dynamic characteristics of the models are not given. In these models, the winter club of bees is too simple - a porous medium and the density of which does not depend on temperature. In fact, the hives itself is a ventilation power plant with a large range of performance and geometric parameters of aggregation of bees have a significant dependence on the ambient temperature. The software product COMSOL allows analyzing a greater number of physical processes in the hive, including changes in humidity in the entire volume of beehives and all the processes taking place in a common multiphysical relationship. The Kuban State Agrarian University is also conducted researches to improve the efficiency of passing the winter period by bees [8, 9]. These studies also use COMSOL with a gradual build-up of the simulated characteristics. The results of these studies are schematic solutions of heater control systems and recommendations on the designs and materials of hives.

It is natural to assume that using the COMSOL environment and developing refined mathematical models it is possible to obtain more adequate solutions for temperature fields in the hive, changes in humidity in certain places of the hive, physical parameters of the bee families. Knowledge of thermophysical processes in the hive will allow developing an optimal system of winter electric heating, which will not lead bees out of the passive state ahead of time, will not allow sharp fluctuations in the temperature of the internal air, and will adjust the power supplied to the heaters without a temperature sensor inside the hive.

2. Method

Bees, assimilating honey, in the process of breathing absorb oxygen from the air and emit carbon dioxide and water. On average, to remove 40 grams of water from the hive released by the bee family for one winter day, you will need about 10 m^3 of air, and this leads to significant heat losses through ventilation. On the basis of the calorific value of honey [4, 7] it was found that the allocation of power of 1 W corresponds to the consumption of honey by bees of 7.65 g per day or 0.32 g per hour. The heat output of bees depends on the ambient temperature [6, 7, 8] and the dependence of the heat output of bees on the outside temperature has a nonlinear form. The approximation of the graphs given in the literature allowed the energy characteristic of 1000 bees of winter aggregation depending on the air temperature T to be expressed by the following equation [9]:

$$P_{bee1000} = 0.00107 \cdot T^2 - 0.0068 \cdot T + 0.307 \quad (1)$$

In winter the average bee family has 15.000 bees, so the equation for the heat output of the bee family P_{bee} will look like this:

$$P_{bee} = 0.016 \cdot T^2 - 0.1 \cdot T + 4.61 \quad (2)$$

In research it is better to use the specific power produced by bees. Divide the obtained expression on the volume of beehives, V_{bee} which is about 0.005 m^3 for present amount and we will obtain the following expression for specific power:

$$Q_{bee} = \frac{P_{bee}}{V_{bee}} = \frac{0.016 \cdot T^2 - 0.1 \cdot T + 4.61}{0.005} = 3.2 \cdot T^2 - 20 \cdot T + 922\,. \quad (3)$$

An equation to determine the necessary air consumption by bees to remove moisture formed in the hive [8]:

$$Q_{air} = \frac{q_{H_2O}}{A_{out} - A_{in}} \quad (4)$$

where q_{H_2O} - water released in the result of forage oxidation, g/h; A_{out}, A_{in} - absolute moisture load of outlet and inlet air, g/m^3.

Given that the amount of water released as a result of oxidation of the feed is about 68 of the feed consumption [7, 8] and the power of 1 W is released at the rate of honey consumption of 0.32 g/h, the expression for air flow given the formula 2 can be represented as follows:

$$Q_{air} = \frac{0.0034 \cdot T^2 - 0.0216 \cdot T + 1}{A_{out} - A_{in}} \quad (5)$$

The relative humidity of air coming directly from the hives will be 100%. According to the literature, the temperature of the output air from the cluster of bees is equal to the temperature of the hives' crust and is at the level of 10ºC to 15ºC. Then the absolute humidity of the output air will be at the level of 9.4-12.8 g/m^3. Naturally, a lower value will correspond to the minimum outdoor temperature (minus 30ºC), a higher value - the maximum temperature (+15ºC). We assume that the dependence of the absolute humidity of the output air on the outside temperature has a linear form. Statistics of meteorological data for the Krasnodar Territory shows that the average relative humidity in winter is 80%. There was the following approximating equation for air consumption rate on the basis of tables of transfer of relative humidity into absolute:

$$Q_{bair} = \frac{0.0034 \cdot T^2 - 0.0216 \cdot T + 1}{A_{out100} - A_{in80}} = \frac{0.0034 \cdot T^2 - 0.0216 \cdot T + 1}{(0.007 \cdot T + 11.5) - (0.0065 \cdot T^2 + 0.3 \cdot T + 4.03)},\ m^3/h\,. \quad (6)$$

We consider the maximum density of hives at the temperature of environment minus 30°C, minimum density – at 0°C. The dependence of bee density from inner temperature is linear and so the corresponding equation for bee density ρ_{bee} will be as follows:

$$\rho_{bee} = 243 - 8 \cdot T \quad (7)$$

The coefficient of the specific heat conductivity of the bee mass λ_{bee} depends on bees' density in the hives. So, the heat conductivity rises from $7.6 \cdot 10^{-4}$ Wt/cm·K to $3.0 \cdot 10^{-3}$ Wt/cm·K with increase of density [7, 8]. Then, the coefficient of heat productivity will be changed in linear due to the equation:

$$\lambda_{bee} = 0.076 - 0.0017 \cdot T\,. \quad (8)$$

So, thermal physical characteristics of winter hives can be presented by the following system of equations:

$$\begin{cases} \rho_{bee} = 243 - 8 \cdot T \\ \lambda_{bee} = 0.076 - 0.0017 \cdot T \\ P_{bee} = 0.016 \cdot T^2 - 0.1 \cdot T + 4.61 \\ Q_{air} = \dfrac{0.0034 \cdot T^2 - 0.0216 \cdot T + 1}{(0.007 \cdot T + 11.5) - (0.0065 \cdot T^2 + 0.3 \cdot T + 4.03)} \end{cases} \quad (9)$$

This system of equations is a thermophysical model of the main parameters of the microclimate in the hive. Bees maintain these parameters of the microclimate inside the hive by changing its density, internal ventilation, heat release when consuming honey. The need for enhanced ventilation is associated with the need to remove moisture formed as a result of eating honey. In this case, the source of energy is honey. When the ambient temperature decreases, bees are forced to eat more honey, which leads to more moisture and therefore they have to increase ventilation which takes out heat.

The system of equations (9) should be added by temperature dependences of heat transfer according to Fourier equations. To describe the motion of air mass flows, it is necessary to use the Navier-Stokes equations. In this case, the systems of equations of the air movement behind the hives and inside them will be separate. Modeling of changes of the humidity regime was carried out in regard with the processes of diffusion and adsorption. Changing the humidity regime is due to the withdrawal of moisture from the club bees. As already noted, when consuming honey, bees secrete a lot of moisture, and therefore the air comes out of the hives with 100% humidity. Wooden elements of the hive - frames and body are porous structure and these structures are able to absorb moisture. The equations representing the process of diffusion and convection were described due to laws of Fick, Navier-Stokes, Darcy. The solutions of obtained mathematical models were carried out in the COMSOL 5.4 package. The studies were carried out in regard with the multiphysical connection "Heat Transfer" and "Laminar Flow", which allowed to calculate simultaneously the thermal processes and the speed of movement of air masses. The analytical unit "Transport of Diluted Species" analyzed the processes of moisture transfer and adsorption of hive elements. At the bee family, air areas were introduced for the entry and exit of air currents. The analytical dependence of the input and output pressures on the planes of the bee family was determined by running the obtained model at different ambient temperatures. Bees in the winter families transmit heat not only due to thermal conductivity, but also due to convection. Therefore, a correction for the thermal conductivity of bees through the Nusselt criterion is introduced.

3. Results

The equations of this model were taken into account in the development of general models of the state of winter bee aggregation and microclimate parameters [9]. The solution of all obtained mathematical models was made with the help of Comsol software product. Initially, a geometric model of a winter beehive was developed (Figure 1).

Modeling was carried out for a stationary mode at different outdoor temperatures from +15°C to -30°C. In Figure 2, there is the temperature field **a** in the cross section of the hive along the central pathway, and in Figure 2.**b** - the temperature field made by cutting through the fourth frame counting from the central pathway (last frame occupied by the beehive). The images show that some of heat goes out through the central bee entrance together with the air removed by the bees. These figures assume that the lowest temperatures are in the lower part of the hive, and higher – in the upper.

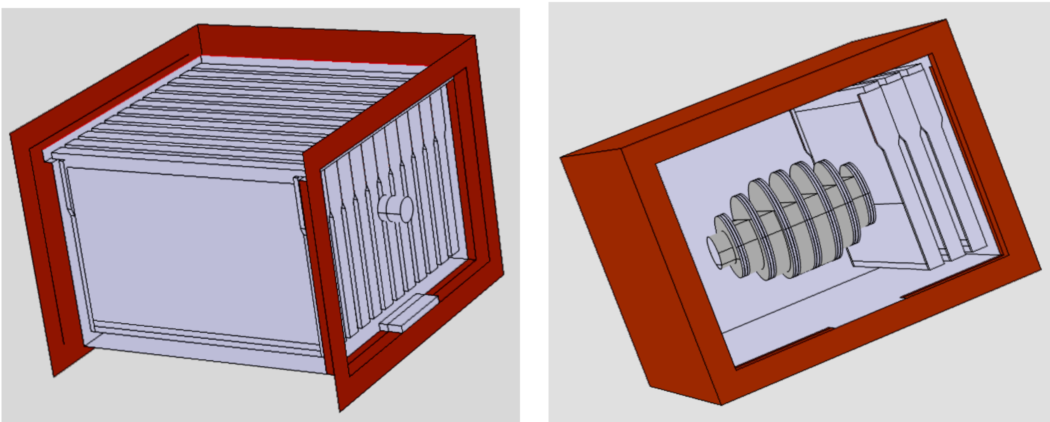
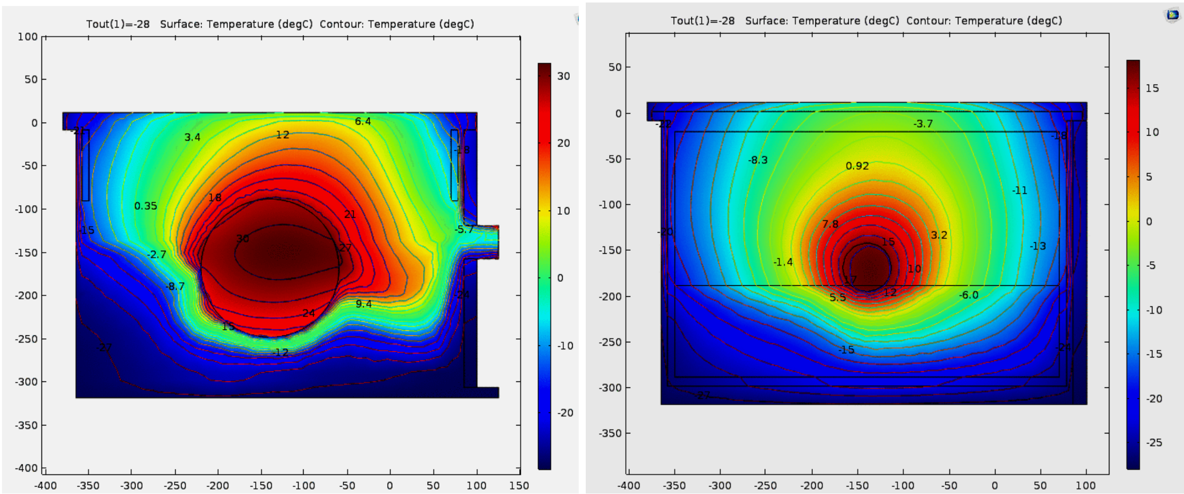


Figure 1. Types of geometric model of the object of research with frames (left) and type of winter hive (right)

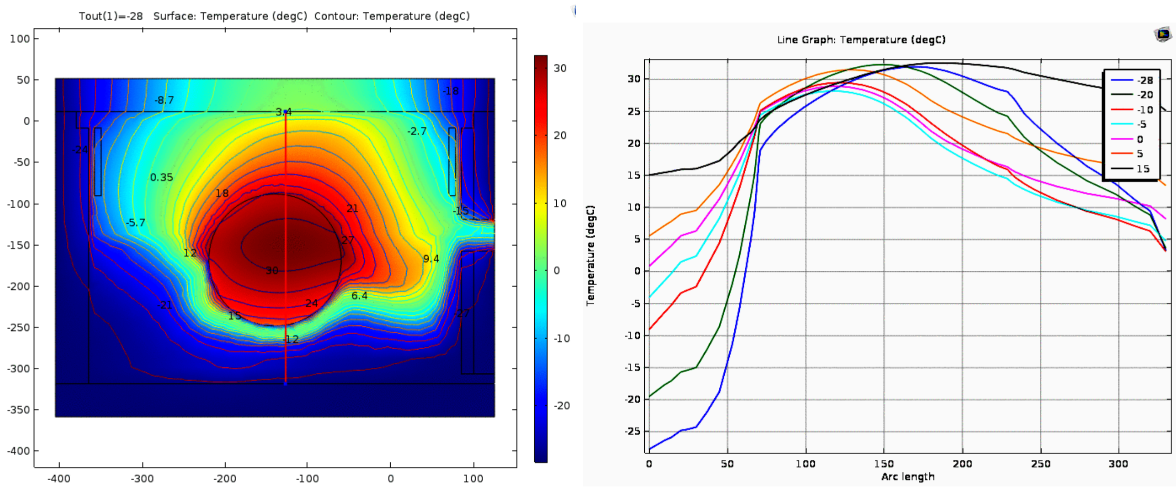


a) b)

Figure 2. Image of temperature fields in the section along the central and extreme frame occupied by the bees

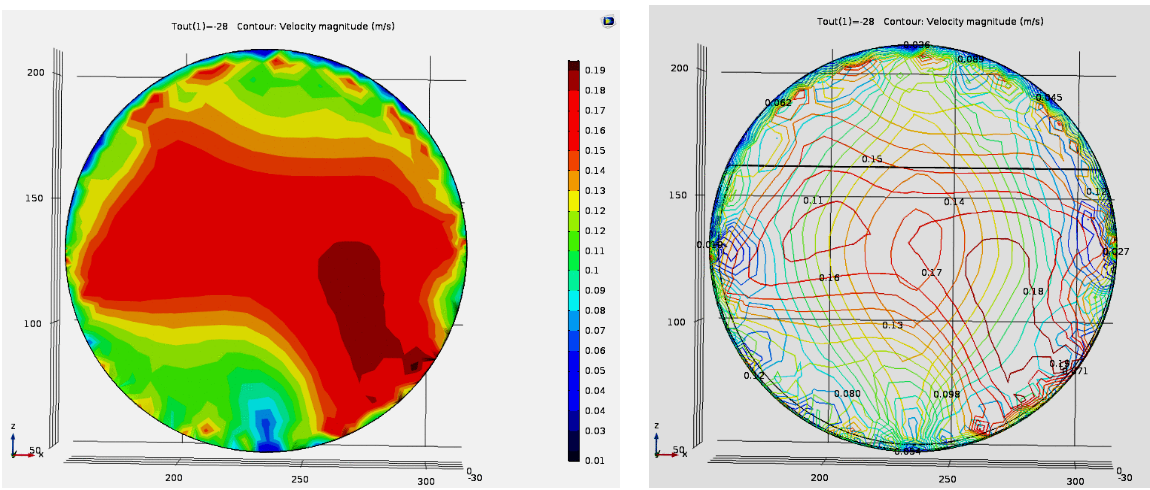
There was the analysis of the temperature distribution in the central pathway on the vertical line (Figure 3) and horizontal lines, at different ambient temperatures. Studies show that despite large changes in temperature outside the beehives, it is maintained inside a fairly stable positive temperature at the level of +25ºC to +32ºC. In the beehives, the temperature is uneven and there are pockets of elevated values, but not more than 34ºC, which is also confirmed by previously published data in the literature. The temperature data obtained confirm the correctness of the formulas used and the validity of the assumptions made.

Analysis of air velocities in individual fragments of beehives (Figure 4) shows that the velocities within the cross section are not the same. For example, there are areas where the air velocity is 0.18 - 0.19 m/s and it is quite high values. On the other hand, the lowest speed is observed at the periphery of the beehives and in its upper part - 0.04-0.06 m/s. This distribution is correct from a biological point of view – at the edge of the beehive the bees are at low temperatures and their life processes are slowed down. At the same time inside the beehive the temperatures are high, bees are more active and ventilate their cluster with greater intensity. As already noted, if only the bee, located in the outer crust, is strongly cooled down, then it goes into the inside, where it warms and gains food.



a) b)

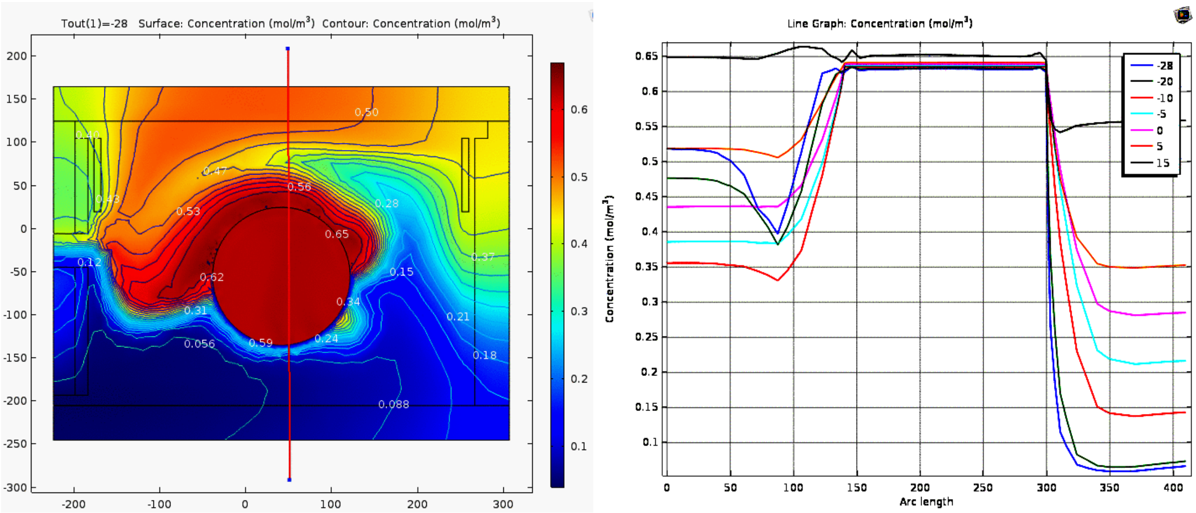
Figure 3. Representation and graph of temperature distribution along the central pathway and vertical line



a) b)

Figure 4. Representation and values of air velocities inside of fragments of the beehives at the temperature of external air **-** 28°C

Figure 5 shows the distribution of moisture concentration along with the structural elements of the hive (wood), where it is seen that the wooden elements are saturated with moisture in accordance with the humidity of the boundary air. The graph of the distribution of moisture concentrations at different ambient temperatures along the vertical line of the image Figure 5.*b* shows the following. The moisture concentration inside the beehives is constant, and at the exit it varies from 0.35 to 0.65 mol/m^3, depending on the external temperature.



a) b)

Figure 5. Representation of distribution of relative moisture of inner moisture inside and near beehives

4. Discussion

The solution of thermophysical models in the COMSOL allows you to see the critical zones inside the hive in terms of temperature and humidity. Images of air velocities confirmed a large range of their changes in temperature fluctuations of the surrounding air. Modeling of processes at the change of temperature of external air from - 30ºC to +10ºC showed the adequacy of the model on temperature both inside and outside its limits. The results of the models' solutions on humidity showed the zones of increased moisture content in the hive. These data are confirmed by the practice of beekeepers. Systematization of the obtained results confirms the assumption that there is no need to install a temperature sensor inside the hive. Studies of the thermal resistances of the elements of the hive show their insignificant influence on the microclimate of the internal environment in the beehives.

The analysis of the received images on humidity allows recommending establishing additional exits of damp air in ceiling laths of the beehive. Images of temperatures inside the hive indicate the need to place heaters at the bottom of the hive and install at least three pieces with different heat power. Further studies of the models need to be carried out with the placement of heaters in the hive and the adjustment of their power. It is required to optimize the output power of each heater depending on the outside temperature and the criterion of minimum temperature fluctuations inside the hive. It is necessary to carry out the modeling of thermophysical processes in a non-stationary mode taking into account heat capacities of physical objects entering the hive.

5. Conclusion

There was an approximating parabolic equation of the energy characteristic of 15.000 bees of winter aggregation depending on the ambient temperature. The equation is derived to determine the necessary air flow by bees to remove moisture formed in the hive, which also allows to take into account the statistics of weather data.

Based on the obtained thermophysical equations and using the Fourier, Newton-Richman, Fick, Navier-Stokes, Darcy equations, mathematical models of the stationary regime describing the processes of heat and moisture distribution in the hive are determined.

The Comsol modeling was used to obtain solutions of mathematical model equations. Images of temperature fields confirmed the high thermal insulation ability of bees. The temperature field on the section through the fourth frame counting from the central pathway shows that part of heat goes out through the central bee entrance together with the air removed by bees. Images of temperature fields confirm the assumption that the lowest temperatures are at the bottom of the hive, and higher – at the top.

Despite the large temperature changes outside the beehives, inside it is maintained a fairly stable positive temperature at the level of +25ºC to + 32ºC. In the beehives, the temperature is uneven and there are pockets of elevated values, but not more than + 34ºC, which is not dangerous for bees. The greatest air velocities are observed in the central bee entrance and inside the beehives. The increased humidity of the internal air is present in the upper part of the hive and above the cluster of beehives.

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