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The models of physical processes of bees winter aggregation

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The models of physical processes of bees winter aggregation

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Abstract. The analysis of physical processes happening in beehives was carried out for 15 000 bees in winter aggregation. In the current study changes of bees aggregation volume during winter season as well as bonds between heating, air exchange and humidity were considered. Simulation of physical in-hive processes was carried out with the help of software Comsol 5.3. Temperature fields analysis confirms the availability of the high thermal insulation ability of bees. On the surface of the bees aggregation the temperature is +12°C. In spite of temperature fluctuations outside the aggregation, inside of the latter temperature is maintained at the level of +25°C...+32°C. Within the aggregation temperature is distributed uneven, and there are zones of higher temperature values not exceeding +34°C, which is not harmful for bees. Analysis of air exchange processes demonstrates that the air velocity near the beehive entrance is 0.03...0.1 meters per second, and in the central inlet – 0.12...0.17 meters per second. The highest air velocity values – exceeding 0.19 meters per second – are achieved inside of the bees aggregation. Humidity level within beehives is uneven. Identity of thermal fields obtained with thermal camera and results of the simulation demonstrates the high level of its concordance.

1. Introduction

To overcome winter season is crucial for beekeeping - efficiency of bee family during the rest of a year, particularly spring honey harvest, depends on it. There are many studies devoted to this topic [1-7]. Thorough analysis done with the help of modern software was carried out by V.A. Toboev, E.K. Yeskov, M.S. Tolstov [8-12]. The peculiarity of winter condition of bees is its ability for aggregation and maintaining of the internal temperature at the level of 24...32°C in spite of the wide range of outer temperature fluctuations. At the end of winter season brood appears, and bees increase internal temperature up to 34°C. Rise of the temperature happens because of honey consumption by bees and permanent ventilation of its aggregation. In spite of huge amount of studies around this topic, the further investigation of in-hive physical processes is required. The necessity of a complete picture of bees life activity is caused by the need to increase the honey production in Russia. Up to now, there are no exact recommendations concerning the amount of honey required for supporting of bees vital activity during the winter season, how the in-hive ventilation system should be designed, etc. It is especially important for winter heating due to the necessity to choose a proper operation mode of heaters. The optimal mode is important because overheating could invoke redundant honey consumption, and provoke a queen for oviparity during cold season which will lead towards death of a whole family. Thus, such investigation should be carried on in order to create optimal conditions for bee families during the winter, and to prevent high temperature fluctuations inside of beehives. There are huge differences in ways of wintering depending of geographical location of bee families. For example, peculiarities of bees wintering at North Caucasus are the following: late bees aggregation, wide range of temperature fluctuations during autumn and winter, early appearance of brood. The objective of the study is to develop the models of in-hive physical processes, examine results of simulation and compare it with thermal camera shots.

2. Theoretical analysis

For analysis of in-hive physical processes we have considered 15000 bees located in Dadant beehives equipped with 12 wax frames. During the winter season bees are collected together as a sphere. We have represented a winter bee-aggregation as separate cylinders of different sizes which, assembled together, resemble a sphere. During the winter bees permanently ventilate its aggregation in order to eliminate excess of moisture - a result of honey consumption. As soon as the ambient temperature is increased, the density of the bees aggregation decreases, and the distance between bees is increased. In order to simulate the air flow through the aggregation, the pathways between frames (further in the text - pathways) were split onto air cylinders (two cylinders per a pathway) with varied height. The volume of these cylinders is equivalent to the overall volume of air per pathway where bees are located. We have assumed that there is a linear relation between the density of bees and outside temperature. The correspondent equation will look as follows:

$$\rho_{bee} = 243 - 8 \cdot T_0 , \tag{1}$$

where T_0 — temperature of outside air, ρ_{bee} — density of bees aggregation.

Heat transfer coefficient of bees λ_{bee} depends on density of its aggregation – if the coefficient increases, then thermal conductance also increases, on average from $7.6 \cdot 10^{-2}$ W/(m·K) to 0.126 W/(m·K) [6, 7, 13]. It means that heat transfer coefficient also will change linearly, in accordance with the equation:

$$\lambda_{bee} = 0.076 - 0.0017 \cdot T_0 , \tag{2}$$

We can assume that heat transfer of bees in cells will be influenced by heat conductivity only, and heat transfer of bees located on pathways – through heat conductivity and internal convection in the beehive.

The peculiarity of such analysis is consideration of changing volume of bees aggregation during wintering. In winter density of the aggregation changes, which means that the radius of the aggregation sphere changes due to the ambient temperature fluctuations.

It is well known, that the plot heating power versus ambient temperature is parabola [6, 13, 14]. For the observed case (15000 bees) the approximation equation looks as following:

$$P_{bee} = 0{,}016 \cdot T_0^2 - 0{,}1 \cdot T_0 + 4{,}61 . \tag{3}$$

For the further analysis the power density created by bees is required. We have divided (3) by aggregation volume and obtained the equation for intensity of heat generation:

$$Q_{bee} = \frac{P_{bee}}{V_{bee}} = \frac{0{,}016 \cdot T_0^2 - 0{,}1 \cdot T_0 + 4{,}61}{0{,}005} = 3{,}2 \cdot T_0^2 - 20 \cdot T_0 + 922 \ , \tag{4}$$

where V_{bee} – volume of the aggregation, V_{bee} = 0.005 m^3.

Knowing that at the honey consumption rate of 0.32 g/h the power of 1 W is released [6, 15], the equation for feed consumption rate in winter time is the following:

$$G_{bee} = 0{,}005 \cdot T_0^2 - 0{,}032 \cdot T_0 + 1{,}475 \ . \tag{5}$$

In [7, 13] the equation for required air flow for moisture elimination is demonstrated:

$$Q_{air} = \frac{q_{H_2O}}{A_{out} - A_{in}} \ , \tag{6}$$

where q_{H_2O} – share of moisture released during the feed oxidation, g/h; A_{out}, A_{in} – absolute moisture content of outgoing and incoming air flow respectively, g/m^3.

Amount of water released during the feed oxidation could be calculated as following:

$$q_{H_2O} = 0{,}68 \cdot G_{bee} \tag{7}$$

Using the charts for transformation relative moisture into absolute moisture, we have obtained the following approximation equation for calculation of required air flow (m^3/h):

$$Q_{bair} = \frac{0{,}0034 \cdot T_0^2 - 0{,}0216 \cdot T_0 + 1}{A_{out100} - A_{in80}} = \frac{0{,}0034 \cdot T_0^2 - 0{,}0216 \cdot T_0 + 1}{(0{,}007 \cdot T_0 + 11{,}5) - (0{,}0065 \cdot T_0^2 + 0{,}3 \cdot T_0 + 4{,}03)} \tag{8}$$

Simulation of in-hive physical processes was carried out in Comsol 5.3 Multiphysics. The initial and boundary conditions for modeling were also established there. The obtained equations for calculation of geometrical and physical parameters were entered into the respective program blocks.

The whole analysis was done for the stationary mode. The generic mathematical model describing in-hive thermal processes is represented as following:

$$\begin{cases} \rho_{air1} \cdot c_{air1} \cdot u_{airr1} \cdot VT + \rho_{air2} \cdot c_{air2} \cdot u_{air2} \cdot VT + Vq_{air1} + Vq_{air2} \\ + \nabla q_{wood} + \nabla q_{hc} + \nabla q_{emptyhc} + \nabla q_{bee} Nu = Q_{bee} \\ \lambda_{bee} = 0{,}0076 - 0{,}0017 \cdot T_0 ; \rho_{bee} = 243 - 8 \cdot T_0 \\ Q_{bee} = 3{,}2 \cdot T_0^2 - 20 \cdot T_0 + 922 \end{cases} \tag{9}$$

where ρ_{air1}, ρ_{air2} – density of incoming (block 1) and passing through the bees aggregation (block 2) air flow respectively; c_{air1}, c_{air2} – thermal capacity of air flow in block 1 and air flow in block 2 respectively; u_{airr1}, u_{air2} – velocity fields of air flow in block 1 and air flow in block 2 respectively; q_{air1}, q_{air2}, q_{wood}, q_{hc}, $q_{emptyhc}$, q_{bee} – densities of waste heat flows caused by heat transfer in air block 1 and air block 2, wooden elements, honey cells, empty cells and bees aggregation respectively, W/m^2; Nu – Nusselt number.

The equation (9) describes the heating processes within beehive and within bees aggregation as well. The temperature inside the club is always positive.

In stationary laminar mode the mathematical model of air mass movement could be represented as follows:

$$\begin{cases} \nabla \cdot (\rho_{air1} u_{air1}) + \nabla \cdot (\rho_{air1} u_{air1}) = 0 \\ 0 = \nabla \cdot \left(\mu \left(\nabla u_{air1} + (\nabla u_{air1})^T - \frac{2}{3} \mu (\nabla \cdot u_{air1}) I \right) \right) + \nabla \cdot \left(\mu \left(\nabla u_{air2} + (\nabla u_{air2})^T - \frac{2}{3} \mu (\nabla \cdot u_{air2}) I \right) \right) \\ u_{in} = \frac{0{,}0034 \cdot T_0^2 - 0{,}0216 \cdot T_0 + 1}{\left[(0{,}007 \cdot T_0 + 11{,}5) - (0{,}0065 \cdot T_0^2 + 0{,}3 \cdot T_0 + 4{,}03) \right] \cdot 1{,}44 \cdot 10^{-3}} \\ - p_1 = -pI + \mu \left(\nabla u_{air\,in2} + (\nabla u_{air\,in2})^T - \frac{2}{3} \mu (\nabla \cdot u_{air\,in2}) I \right) \\ p_2 = -pI + \mu \left(\nabla u_{air\,out2} + (\nabla u_{air\,out2})^T - \frac{2}{3} \mu (\nabla \cdot u_{air\,out2}) I \right) \end{cases} , \tag{10}$$

where p - pressure, Pa; μ — dynamic viscosity, Pa·s; I – unit vector; u_{in} – air velocity at the entrance in a beehive; p_1, p_2 – pressures at the incoming and outgoing surfaces of the air block; $u_{air\,in2}$, $u_{air\,out2}$ – air velocity at the entrance to and exit out of a bee aggregation.

The pressure values, p_1 and p_2 were determined by preliminary iterations of different outdoor temperature values. The criterion for fixing the pressure values is the temperature at certain points of the club. As a result of such iterative calculations, approximations for the pressure at the entrance to the bee club were obtained.

$$p_1 = 2 \cdot 10^{-6} \cdot T_0^6 + 10^{-6} \cdot T_0^5 + 6 \cdot 10^{-6} \cdot T_0^4 - 0{,}0001 \cdot T_0^3 + 0{,}001 \cdot T_0^2 + 0{,}19 \cdot T_0 + 0{,}159 \tag{11}$$

Using this equation, the modeling of the main thermophysical processes occurring in the hive and in the bee club was carried out. The temperature at the edge of the club did not fall below 10-12 °C, and inside the club was no higher than 30-33 °C, which corresponds to the data given by numerous authors.

Simulation of humidity changes was carried out considering convection, diffusion and adsorption based on Fick law, Navier-Stoks equation, Darcy's law. The generic model of humidity changes considering diffusion and convection could be represented as following:

$$\begin{cases} \frac{\partial c_{water}}{\partial t} + \nabla \cdot \left(- D_{water} \nabla c_{water}\right) + u \cdot \nabla c_{water} = 0 \\ j_1 = -D_{water} \nabla c_{water} + u \cdot c_{water} = 0 \\ \frac{\partial}{\partial t}\left(\rho_b \cdot c_{Pwater}\right) = \nabla \cdot \left(D_e \nabla c_{water}\right); \rho_b = \left(1 - \varepsilon_p\right)\rho \\ j_2 = -D_e \nabla c_{water} \end{cases}, \quad (12)$$

where c_{water}, D_{water} – concentration and diffusion coefficients of water respectively; j_1, j_2 - diffusion flows in gas and solid phases respectively; c_{Pwater} – concentration of moisture in solid phase; ρ_b – equivalent density of solid matter, $\rho_b = \left(1 - \varepsilon_p\right)$; ε_p – porosity of the material; D_e – efficient share of diffusion coefficient.

We have obtained three mathematical models (9), (10), (12) which are interconnected via physical parameters. These models describe generic in-hive processes: heating, humidity, air flow.

3. Research results and discussion

We have carried out simulation of the stationary mode for several values of critical temperatures of ambient air: –28ºC, –20ºC, –10ºC, –5ºC, 0ºC, +5ºC, 15ºC [16-18]. For the temperature – 28°C the following temperature fields were obtained – figure 1. At the figure 1 it is visible that the significant in-hive space is covered by sufficient negative temperatures – from –15°C to –20°C. At the same time the temperature of bee aggregation is maintained at the value of +29°C.

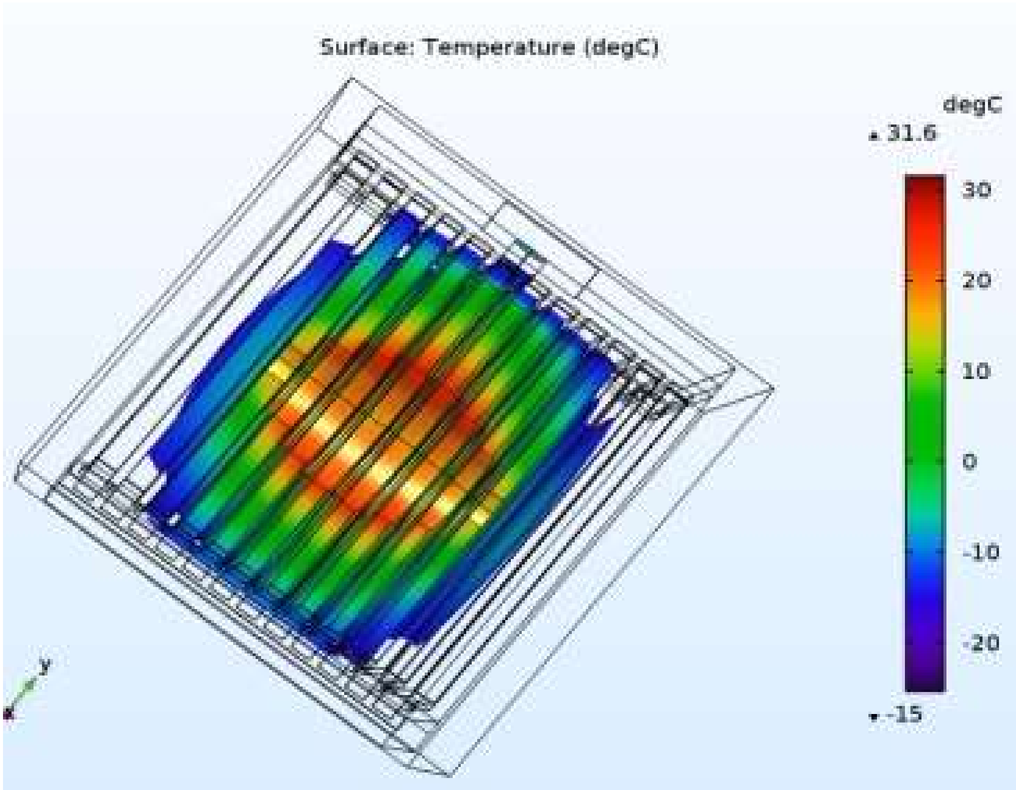

Figure 1. Temperature fields of a beehive.

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At the sections of a beehive done perpendicularly to the front wall or parallel to it (figure 2) it is visible that heat partially goes out through the central inlet together with eliminated air. At the figure 2 the zones of maximal temperature are visible as well. These pictures prove assumptions that low temperature is concentrated at the bottom part of a beehive, and higher temperature is located in upper part of a beehive.

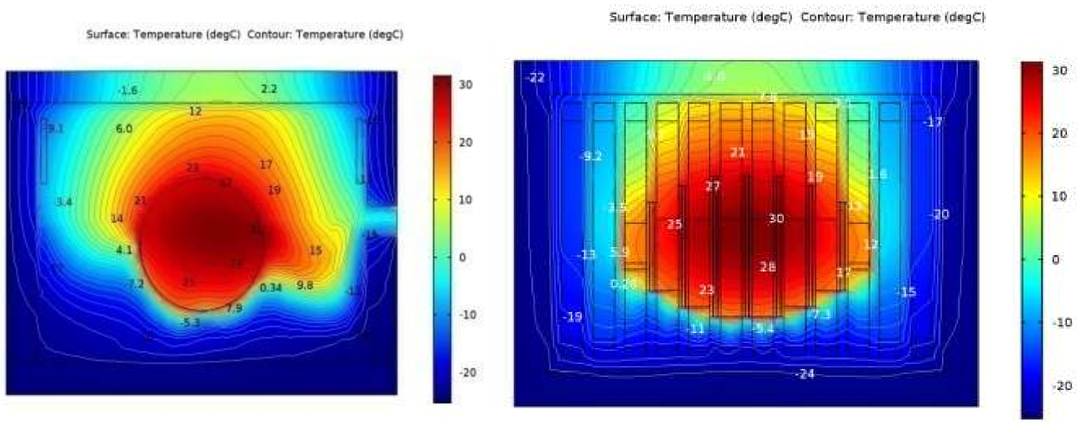

Figure 2. Temperature fields of a beehive at sections.

The studies described below were devoted to the analysis of in-hive air flow. At the figure 3 the air velocity and air path are represented from different observation points for the ambient temperature of – 25°C. It was defined that air velocity at the beehive entrance is 0.01...0.02 m/s, and at the exit from the beehive (central inlet) – 0.12 m/s. Trajectories of incoming air show that air comes in through the bottom inlet and is distributed further between frames and moves along the rear wall.

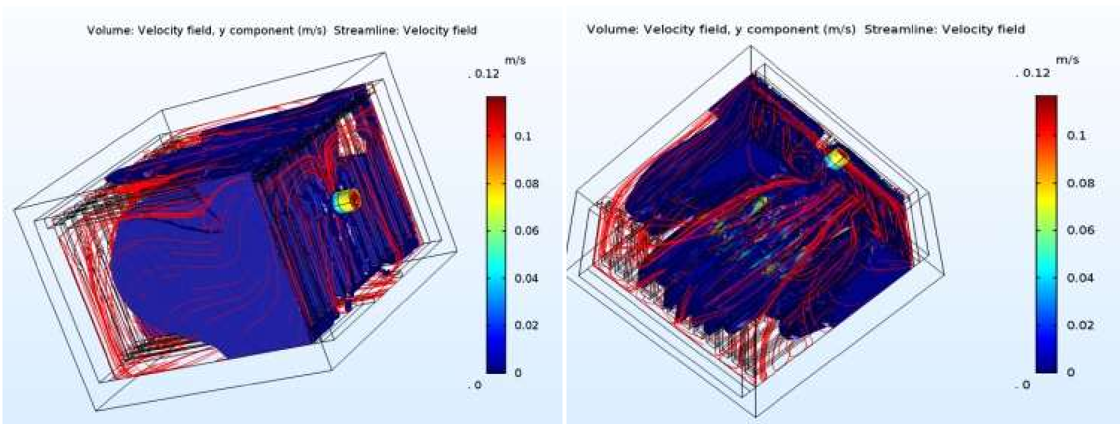

Figure 3. Beehive views demonstrating in-hive air velocity.

Analysis of the trajectories and air velocity in separate zones of the bees aggregation shows that air velocity within the aggregation is uneven – there are zones where air velocity is 0.15...0.17 m/s, which is a quite high value. The smallest value of air velocity is observed at the periphery of the aggregation as well as at the upper part of the latter – 0.04...0.06 m/s. It is reasonable from the biological point of view: at the edge of the aggregation bees are exposed to the low ambient temperature and its vital processes are slowed-down. Nevertheless, there are zones of high air velocity at the edge of the aggregation – these are zones of incoming air. Within the aggregation temperature is high, and bees actively ventilate it.

Studies of moisture distribution within a beehive shown how ambient air with humidity of 0.04 moles per cubic meter comes inside the beehive from the bottom inlet. At the upper point of the beehive moisture concentration reaches the values of 0.5...0.6 moles per cubic meter, which is a result of moisture elimination out of the aggregation. At the figure 4 the central section of a beehive is shown with moisture distribution field. It is visible that the highest moisture concentration is located inside the bees aggregation as well as at the point where humid air leaves the aggregation. Incoming air as well as bottom zone of the beehive have the lowest moisture concentration.

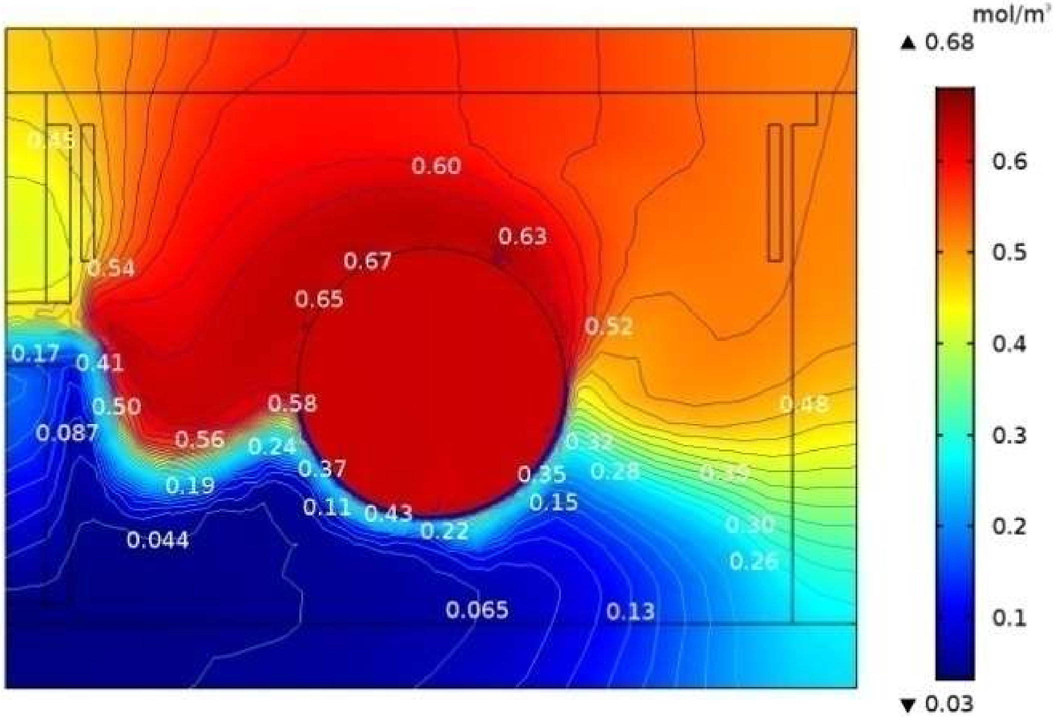

Figure 4. Central section of the beehive with moisture distribution field.

Analysis of moisture distribution considering properties of constructive elements of the beehive (wood) proves that wooden parts are saturated with moisture of boundary air. Absorbed at wooden parts moisture is visible, especially at the upper part of the beehive – this phenomena meets reality (it is observed in spring time while opening beehives).

Based on obtained simulation results the following conclusions were done. Results of simulation and analytical expressions for thermal parameters are in concordance with the thermograms done by other research groups [15, 19, 20].

Experimental studies of microclimate within beehives were done at the apiary located at Mostovskoy district, Krasnodar region. Thermal fields were studies at a beehive of Dadant type with 12 frames, in autumn season the bee family was located at 10 frames. The next stage of the experiment was thermal shot of ceiling of the beehive without lid. Thermal shot was done during winter season at the different levels of ambient temperature. The thermogram done at the temperature –3°C was compared with results of the simulation relevant for the same temperature (figure 5).

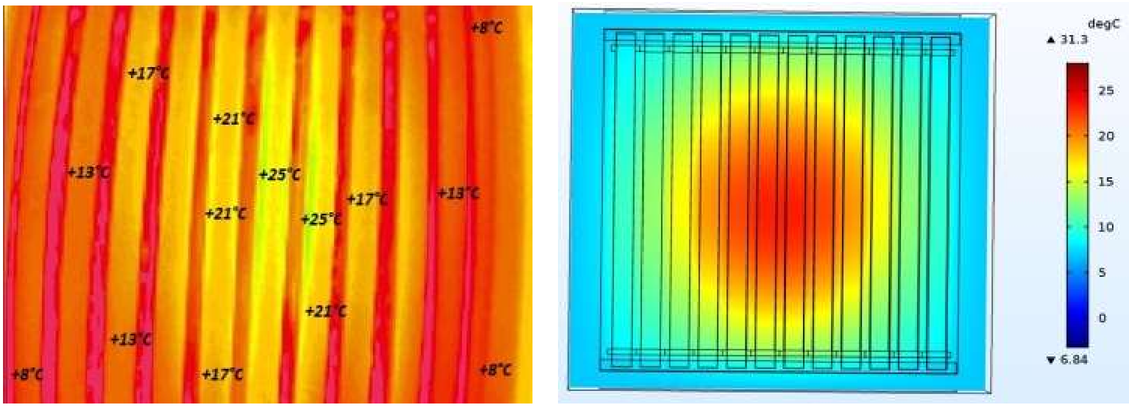

Figure 5. Thermograms of the beehive surface without lid (on the left) and results of simulation (on the right).

Concordance of thermograms and results of the simulation was verified for the beehive without rear wall. Thermal shots as well as simulation were carried out at the ambient temperature –8°C. At the figure 6 the obtained thermograms are presented. It is visible that temperature fields are similar, but the zone where bees are located looks wider at the thermal shot. This difference could witness that bees cover more frames, and most likely that aggregation was expanded parallel to the bottom of the beehive. At the same time it is visible that temperature values at the thermogram and simulation picture are equal, and heat distribution has similar character.

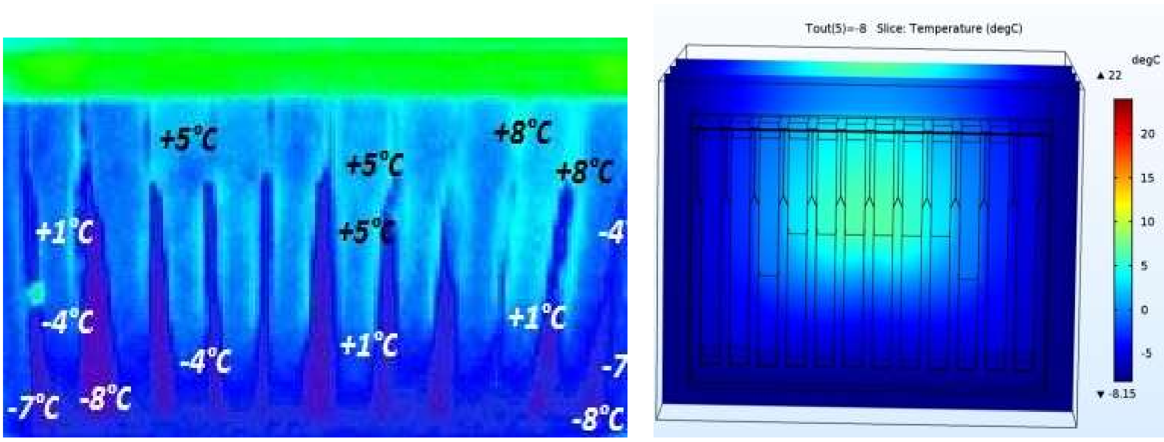

Figure 6. Thermograms of the beehive surface without rear wall (on the left) and results of simulation (on the right).

Experimental study of the temperature field within bees aggregation was carried out in accordance with the following method. Due to the possible harmful impact onto bee families in winter season, the temperature analysis was done through taking out edge frames from the beehive, and rapid thermal shot was done (a frame containing honey has a significant thermal capacity). At the figure 7 thermograms obtained though thermal shot and simulation are represented for the ambient temperature +2°C. It is visible that thermal fields are identic, but experimental shot shows wider zone occupied by bees.

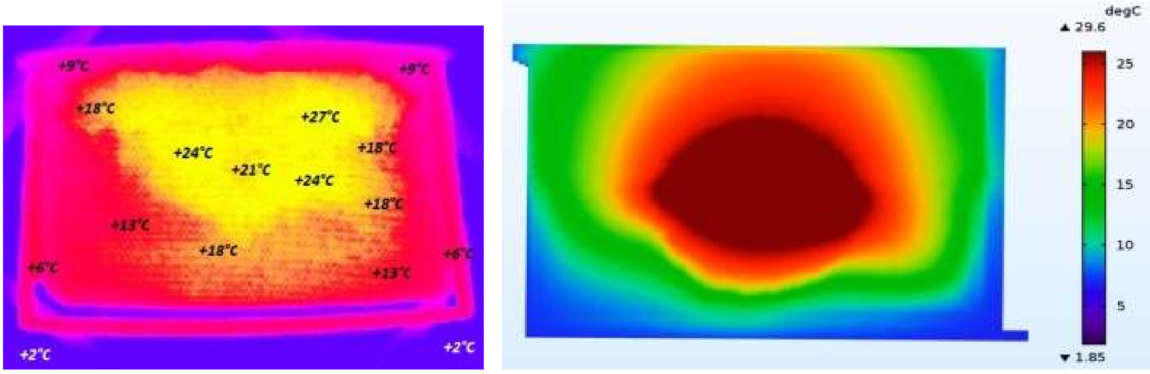

Figure 7. Experimental thermograms (on the left) and results of simulation (on the right) of the frame.

4. Conclusion

The set of equations describing the interconnection of geometrical and physical parameters of bees winter aggregation and ambient temperature is adequate to the real behaviour of bees family. Obtained equations describe the microclimate parameters within bees aggregation considering the changes of its dimension and internal ventilation. Pictures of thermal fields prove the high thermal insulating ability of bees, and it is visible how temperature changes within and outside of bees aggregation. The section of the temperature filed at the fourth frame (counting in the direction from the centre towards walls) demonstrates that significant share of heat is lost through the central inlet together with outgoing air. Analysis of temperature changes inside the bees aggregation confirms the assumption that the lowest temperature is on the bottom surface of the aggregation which corresponds to [13]. Analysis of the in-hive air flow demonstrates that minimal air velocity is observed at the entrance to the beehive, and maximal air velocity is observed at the exit (central inlet) of the beehive. The highest air velocity – over 0.17 m/s – is observed inside of a bee aggregation. Obtained values of air velocity in the separate fragments of the bees aggregation are reasonable from the biological point of view – at the edge of the aggregation bees are exposed to the lower temperatures and its vital processes are slowed-down. At the same time within the aggregation temperature is higher, bees are more active and ventilate more actively. In winter season the moisture distribution is uneven: incoming air at the bottom of the aggregation contains 0.04 mole per cubic meter of moisture, and at the top of the aggregation moisture content is 0.5...0.6 moles per cubic meter. It is caused by the process of moisture elimination out of the aggregation.

Experimental studies of thermal fields within beehives show that obtained thermograms are similar to the results of simulation. Comparison of temperatures in different zones of a beehive has shown that the temperature difference was not more then 2°C. Identity of the thermograms proves the possibility of application of the obtained models for in-hive microclimate analysis also at the other setup parameters (geometry, physical parameters, ambient temperature, quantity of bees). The further development of the models should be done considering a heating device at the bottom of a beehive. An adaptive energy efficient heating system for beehives could be developed on the basis of the obtained models.

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