Models of the Thermal Condition of Winter Aggregation of Bees with Electric Heaters Installed in the Hive

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Abstract. Of on factors of high productivity of a bee family is successful wintering. However, there are problems related to availability of food: in cold season bees may not get honey deposited in the frames located close to the outer hive walls, dramatic spring temperature fluctuations stimulate bees to earlier activity and they may fill the intestinal tract earlier. To promote successful wintering, beekeepers use electric heating. Despite the obvious advantages of additional heating of bees, there are also drawbacks: it is possible to provoke the queen for the early sowing of larvae, increased consumption of honey by the bee family may occur, there are additional costs for the consumed electrical energy. The article considers models of thermal and other physical processes occurring in the hive during the winter. The obtained models allow to: optimize energy costs for heating, reduce temperature fluctuations inside the hive, reduce the energy consumption of bees to maintain the microclimate. Validation of implementation of the algorithms in the system of automatic heating, based on the proposed models, showed the following: there is a good quality match of simulated and empiric temperature fields in the hives, there was a decrease in honey consumption by bees, hazard of drizzle was minimized.

1. Introduction

Nowadays in Russia, unlike countries with developed beekeeping branch, more than 90% of honey is produced on small apiaries with an average number of about 20 bee families. Therefore, honey production is not so much regulated by economic laws as it is dependent on climate conditions. The production and cost of honey is also affected by the availability of modern equipment. Most beekeepers are worried about the answers to the questions: how many bees will successfully pass through the winter, how good will be condition of bee family after wintering, whether the hives have enough food.

A wintering is a test of a beekeeper's professionalism. Parameters of internal microclimate during the winter directly influence the strength of bee family in the end of wintering [1-6]. Good ventilation of the beehive is very important. The bees emit metabolic water vapor, which should be removed from the hive in time. In case of insufficient air exchange, the internal air humidity increases, which leads to condensation on the walls of the hive and frames filled with honey. In such a case, honey fermentation may occur, and consumption of fermented honey by wintering bees may lead to their illness and even death.

The temperature regime inside the hive is also very important. It can be noted that a consistently low temperature is more favorable for bees than its fluctuations. At low temperatures, the bee aggregation simply becomes denser to reduce heat transfer, and bees slow down their life processes. At the same time, bees consume more food to compensate heat loss. Simultaneously, water vapor is released and the
bees need to remove it more actively from the club. Fluctuations of outside temperature during thaws followed by frost, change the physiological condition of bees and the size of their aggregation. Bees start to go into active mode and then return to the hibernation state again. During such periods bees even start to leave the hive to get rid of feces. Some bees are not able to return back to the hive because they have been weakened and frozen outside. Inside the hive, as the hive warms up by the outside temperature, the bees begin to move around the hive in search of food deposits. In this case, the aggregation can be divided into parts, and small groups of bees in remote hive’s corners can die when frosts occur. Thus, spring is the most dangerous season for bees wintering in the wild. Many beekeepers use electric heating during winter and spring. However, inadequate adjustment of the power supply of heaters sometimes leads to negative results. Artificial heating can lead to higher temperatures in the beehive. Excessive heat stimulates increased activity of bees, acceleration of physiological processes in their organisms and increased consumption of feed stocks. If a beekeeper has left insufficient honey in the hive, the whole family may starve to death. In addition, at the end of winter, the queen may start sowing early, and growing winter brood leads to an increased temperature in the hive, increased work of bees resulting in to their weakening, increased honey consumption. It is especially difficult for a bee family to endure cold and frosty weather when brooding, as bees try to keep the larvae warm and do not leave them even at the lack of honey. If honey is not enough or it is located at the remote frames, the bees will not get it and die.

2. Theoretical analysis
In order to obtain mathematical descriptions of the main physical processes in the hive and to model them, a hive on 12 frames was chosen, which housed a family of 15000 bees. This is the average number of a family in the winter period. Initially, a geometric model of the object of study was developed, the form of the one is shown in the Fig. 1. The winter aggregation of bees was presented as an ellipsoid, cut by frames and air gaps where air exchange of bees aggregations take place (Fig. 2). There are three film-type heating elements at the bottom of the hive.

![Figure 1. Geometric model of the hive.](image1)

![Figure 2. Geometric model of the hive with a winter aggregation of bees.](image2)

The geometric dimensions of the ellipsoid were dependent on the surrounding temperature [7, 19]. The dependence was obtained based on data provided in the literature [6, 7, 21] with subsequent approximation of the corresponding graphs. All physical processes were simulated in Comsol® environment. To obtain mathematical descriptions, the corresponding interfaces were used, which were then combined through multiphysical links. Accepting boundary conditions and relevant assumptions, mathematical models of thermal and humidity characteristics of the hive describing in-hive air flow
based on the Navier-Stokes equations were obtained. Thus, the generalized mathematical model describing the thermal processes in the hive is as follows:

\[
\begin{align*}
\rho_{air_1} \cdot c_{air_1} \cdot u_{air_1} \cdot \nabla T + \rho_{air_2} \cdot c_{air_2} \cdot u_{air_2} \cdot \nabla T + \rho_{elh} \cdot c_{elh} \cdot u_{air_1} \cdot \nabla T + \nabla q_{wood} + \nabla q_{hc} + \nabla q_{emptyhc} + \nabla q_{bee} N_u + \nabla q_{elh} &= Q_{bee} + Q_{elh} \\
\lambda_{bee} &= 0.0076 - 0.0017 \cdot T_0; \rho_{bee} = 243 - 8 \cdot T_0 \\
Q_{bee} &= 3.2 \cdot T_0^2 - 20 \cdot T_0 + 922 \\
q_i &= -\lambda_i \Delta T \\
Q_{elh} &= f(T_0)
\end{align*}
\]

where \( \rho_{air_1}, \rho_{air_2} \) – density of incoming (index 1) and passing through the bees aggregation (index 2) air flow respectively, kg/m\(^3\); \( c_{air_1}, c_{air_2} \) – thermal capacity of air flow in block 1 and air flow in block 2 respectively (indoor air and in-aggregation air); \( u_{air_1}, u_{air_2} \) – velocity fields of air flow in block 1 and air flow in block 2 respectively; \( q_{air_1}, q_{air_2}, q_{wood}, q_{hc}, q_{emptyhc}, q_{bee}, q_{elh} \) – densities of waste heat flows caused by heat transfer in air block 1 and air block 2, wooden elements, full honey cells, empty cells and bees aggregation respectively, W/m\(^2\); \( T_0 \) — temperature of outside air; \( \lambda_{bee} \) – bees’ thermal conductivity coefficient; \( \rho_{bee} \) – density of bee aggregation, kg/m\(^3\); \( N_u \) – Nusselt number; \( \rho_{elh}, c_{elh} \) respectively the density and heat capacity of the electric heater; \( Q_{bee} \) – bee heat emission rate; \( Q_{elh} \) – heater intensity.

The main challenge was to obtain the analytic expression of the last functional dependence in the system of equations (1). The difficulties are related to the following limitations: regulation of the central and side heaters should be done separately and according to separate algorithms, the surface temperature of the heater should not exceed 47\(^\circ\)C (so as not to injure bees), from the point of view of operation it is better to consider discrete regulation. In this regard, it was decided to obtain the required dependence by iteration method on the basis of already obtained data on the simulation of thermal conditions in the hive at different outdoor temperatures.

The results of simulation of physical processes in the hive were derived for certain outdoor air temperatures: -30\(^{\circ}\)C, -20\(^{\circ}\)C, -10\(^{\circ}\)C, -5\(^{\circ}\)C, 0\(^{\circ}\)C, +5\(^{\circ}\)C, 15\(^{\circ}\)C. Such temperatures were taken from annual observations in the Krasnodar Region, and this temperature range is most typical for changes in the condition of bees. The Figures 3, 4 show the temperature fields in volume and section of the hive through the central space. From these figures we can see that the maximum temperature is observed in the center of the bee aggregation and reaches values of +30\(^{\circ}\)C, and the minimum temperature is detected at the entrance to the hive and at the located nearby frame and its magnitude is minus 30\(^{\circ}\)C. At the same time, the temperature on the surface of the central heater is +23 \(^{\circ}\)C, and on the surfaces of lateral heaters is about +20 \(^{\circ}\)C. If the external temperature became equal to 0\(^{\circ}\)C, the temperature inside the bee aggregation was equal to +28\(^{\circ}\)C, and the temperature of heaters was about +8\(^{\circ}\)C.

As a result of the presented study, it was found out that at the maximum total power of heaters equal to 15 W (specific power of about 74000 W/m\(^3\)) bees reduce the emission of thermal energy from 3600 W/m\(^3\) to 1900 W/m\(^3\), that is almost two fold. Consequently, the bee family will also reduce honey consumption. However, there are also significant temperature fluctuations inside the hive with a wide range of changes in outdoor temperature. As it was previously noted, any changes in temperature bother bees, they are trying to react adequately. Bees start to consume food intensively, which leads to a rapid clogging of the bees’ intestines and their need to leave home.

Therefore, it is necessary to achieve for minimal temperature fluctuations inside the hive, for example, within the range of 3-5 \(^{\circ}\)C. It is necessary to select the operation mode of the heaters so that with a wide range of changes in ambient air temperature inside the hive, the air temperature would...
change in the narrow range. It is also necessary to control the temperature of the heater surfaces and it is possible not even to supply enough heating for bee family at low ambient air temperatures. By meeting these criteria, the heaters' input power was optimized (Table 2).

| Name of indicators                          | Indicator Values |
|---------------------------------------------|------------------|
| Outside temperature, °C.                   | 0    -5    -10   -15   -20   -25   -30 |
| Central heater power P1, W                 | 1.5  3.5  6.0  8.0  9.5  10.5  11.5 |
| Total power of lateral heaters P2, W       | 3       7     12    16    19    21    23   |

Analysis of the obtained results revealed that the temperature of heaters does not exceed +46 °C (at the temperature per hive minus 30 °C), and the temperature inside the hive changes from +5 °C to minus 1.5 °C when the ambient air temperature changes from 0 °C to minus 30 °C. The distribution of temperature fields at ambient air temperature of minus 30 °C is shown in the Figures 5 and 6.

Figure 3. Temperature fields within the hive.  
Figure 4. Hot fields across the hive.

Table 1. Optimum heater output values at different ambient temperatures.
The moisture content of the hive was also studied. The external air humidity was taken from the average statistical data for the average winter in the North Caucasus (relative humidity 80%). The air entering the hive had a moisture concentration of about 0.04 Mol/m$^3$, while in the upper zone of the hive the moisture concentration is already 0.5-0.6 Mol/m$^3$. This phenomenon occurs due to the removal of moisture from the bee aggregation. Analysis of moisture distribution in the structural elements of the hive (wood), revealed that they absorb moisture in accordance with the humidity of the boundary air. Distribution of moisture inside the hive at different ambient air temperatures shows the following. The moisture concentration inside the hive is constant and varies between 0.62 and 0.65 Mol/m$^3$, and at the top of the hive it varies between 0.65 and 0.35 Mol/m$^3$ (at the low outside temperatures lower values are relevant). At outside temperatures of minus 28°C, the moisture concentration of the incoming air in summer is 0.1 Mol/m$^3$, and at the outlet of the central flight it is 0.5 Mol/m$^3$. At the same time, at the incoming air temperature of +15°C, the moisture concentration is 0.56 Mol/m$^3$, and at the outlet of the central flight is 0.64 Mol/m$^3$. The situation is explained by the originally low moisture content in the incoming air at low temperatures. Bees also consume more honey at this temperature, which results in increased water vapor production as a result of decomposition of honey. Consequently, bees have to increase intensity of ventilation in the aggregation.

3. Research results and discussion

Experimental studies of microclimate parameters in the hives were conducted in winter and spring at a real apiary in Mostovsky district of Krasnodar region. Thermal fields in the hives were studied by a 12-frame infrared camera in the beehive. Thermal imaging was performed on the hive's ceiling surface with the lid and ceiling slats removed. The research was carried out at different outdoor temperatures. Good quality match of thermal fields was obtained. Researching the thermal fields inside the aggregation is dangerous, as opening up the winter aggregation of bees can cause significant damage of the bee family. Therefore, the analysis of the temperature surfaces of interest was carried out by removing the frames adjoining the aggregation and their quick heating (the frame with honey has a significant heat capacity). Figures 7 and 8 show comparative thermograms obtained experimentally and simulated at the same external temperature of 0°C. It is visible that temperature fields practically coincide, but in experiment it is possible to observe also the big zone occupied by bees.

Comparison of energy results was carried out during cold periods of winter of the year 2018. Two hives of the comparable bee families were selected at the apiary. Weight of both hives was monitored during the study period.

![Figure 7. Thermograms obtained experimentally at an ambient temperature of 0°C.](image1)

![Figure 8. Simulated thermograms for ambient air temperature of 0°C.](image2)

One of the hives was equipped with electric heating with optimization of operation mode according to the developed algorithm. Data on ambient air temperatures were recorded and then compared with the meteorological data for the city of Labinsk and they were almost the same. The electric heating was
connected through an electric energy meter with the possibility of recording the obtained readings. The obtained material showed good match of theoretical and experimental values [21, 22].

4. Conclusion
Comparison of the simulated and experimental thermal fields of the beehive interior space showed that the obtained thermograms have a good match. The analysis of temperature values in some places of the hive during modeling and experiment has shown that the relative error does not exceed 12%. The match of thermograms proves the possibility of using the obtained models for the development of algorithms of microclimate control in a hive. If necessary, it is possible to change the control modes depending on other input data, both on hive geometry and parameters of hive’s design, as well as on changes in family strength. The implementation of the heating system on the real apiary according to the proposed algorithms has led to minimum power consumption and good quality of overwintering of heated hives. During the five cold months, the electricity consumption of a heated beehive was 9 kWh, but feed consumption was reduced by 1.8 kg compared to a beehive without heating. In hives with electric heating the number of died bees was minimal - 10-30 bees per family during the winter, and in hives without heating - 100-200 bees.

5. References
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