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In-situ testing of honeybee waste heat - powered energy harvesting system

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Abstract

As a honeybee colony overwinters, it forms a tight cluster to efficiently maintain the essential temperature of up to about 35 °C. A portion of the hence generated heat, which is the result of bees' metabolism, is transmitted through the hive walls towards the cold environment, generating, therefore, a considerable thermal gradient. Based on these considerations, a novel approach to powering an autonomous beehive monitoring system, aimed at utilizing the waste heat generated by the colony, is proposed. The energy harvesting system prototype, comprising thermoelectric generators (TEGs), heatsinks connected by heat pipes, and a suitable step-up DC-DC converter, previously studied via numerical modelling and in a laboratory setting, is tested in this work in-situ. Standard wooden Langstroth hives, occupied by Carniolan honeybees (lat. *apis mellifera carnica*), are thus used in real life conditions in a natural environment. Due to the relatively low power output, typical for low ΔT TEG-based systems, a fitting energy storage solution is also considered. The first field tests of the prototype energy harvesting system are described in this work, with the obtained results showing the viability of the proposed approach, representing therefore the basis for further refinement of the proposed energy harvesting setup, and the development of a functional autonomous hive monitoring system. To concentrate the flow of heat across the harvester, additional hive insulation is also considered.

Honeybee colony, energy harvesting, waste heat, autonomous monitoring system

1. Introduction

An innovative concept, aimed at honeybee hive monitoring, based on harvesting waste heat generated by the colony itself, was recently proposed [1]. The idea is to utilize the metabolic heat produced by the cluster of overwintering bees inside the hive [2-4] to power an autonomous monitoring system [1]. Such a system could be employed to assess the strength of the colony, monitor it during the winter months and, via ultra-low power components and suitable communication protocols, inform the beekeeper of any changes in a selection of measured values, e.g. the temperature distribution and humidity inside the hive [1], [5-8]. Additional sensors may be included, such as miniaturized scales monitoring food stores, microphones aimed at sound signal examination or low power cameras for pest detection. A suitable power management system with smart duty cycles will, therefore, have to be introduced to address the energy needs of the sensors.

Initial in-situ temperature measurements on honeybee colonies occupying single and double LR hives have shown a significant temperature difference between the hive interior and the outside environment. A proof-of-concept device, comprising a single thermoelectric generator (TEG), and two heatsinks connected via copper-water heat pipes, was hence built. Tests conducted in laboratory conditions have shown that, at a temperature difference of ~ 24 °C, ~ 10 mW of power can be generated by this system [1].

In this work, an enhanced energy harvesting - based device for powering beehive monitoring systems is presented. It consists of two TEGs optimized for operation at lower temperature differences. Furthermore, the area of the heatsinks is significantly increased, and the copper-water heat pipes are replaced with methanol ones, which can withstand lower ambient temperatures during in-situ testing.

2. Design and operation of the energy harvesting system

As the bee colony forming the cluster generates heat due to metabolism, warm air rises towards the top of the hive, and the excess heat gradually dissipates through the hive roof into the environment. The waste heat harvesting system, shown in Figure 1, comprises two TEG2-126LDT TEG modules (1) [9], connected in series and placed between the respective hot and cold junctions, where the hot side, i.e., the inner heatsink (2), is positioned above the cluster, while the cold side, i.e., the outer heatsink (3), is located on the outer wall of the hive. These two sinks are connected via methanol heat pipes (4). The harvesting system is integrated into a standard Langstroth top feeder with a ventilation mesh (5), and a natural thermal insulation layer (6) placed around the inner heatsink, to direct the heat flow.

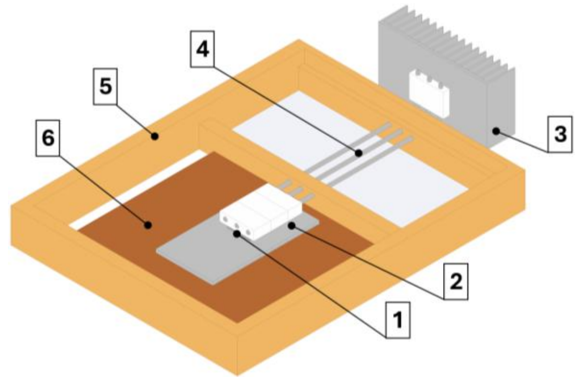


Figure 1. Graphical representation of the main components of the waste heat harvesting system used for in-situ measurements

The deployment of the harvesting system on a Langstroth hive is represented in Figure 2. To capture waste heat, the TEG harvesters (1) are positioned above the hive frames (2) occupied by bee cluster (3). In addition to the insulation layers placed around the inner heatsink (4), a similar layer is located underneath the hive roof (5) to further reduce the heat flow into the environment. The heat flow is thus focused on the inner (hot side) heatsink of the harvesting system (6), while the heat flowing through the device is dissipated via the outer (cold side) heatsink (7), exposed to the environment. Two Al blocks are used as interfaces between the heat pipes and the TEGs on the inside, and the outer heatsink on the outside. All metal-on-metal connections are coated with a thermally conductive compound to eliminate potential air gaps that would act as thermal insulation. The TEGs' hot and cold sides are coated with a graphite layer, thus maximizing heat transfer.

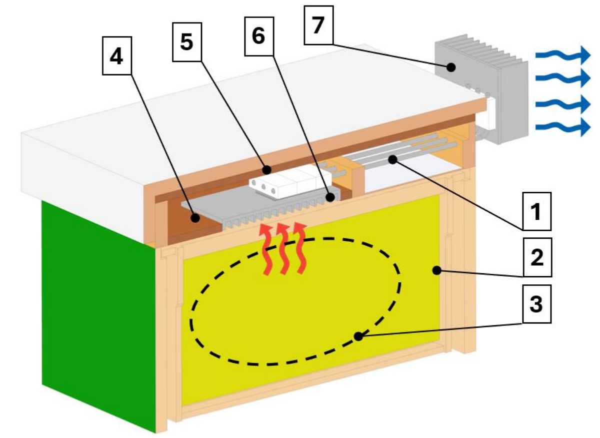


Figure 2. Graphical representation of the harvesting system positioned on the hive, and the heat flow through the system

On both sides of the harvesting system, near the hive wall, the insulating material is trimmed (Figure 1) to allow some of the warm and moist air to escape the hive, facilitating the ventilation of the hive, essential for colony health [2], minimizing thus the impact of the EH system on the hive environment. Furthermore, the whole EH system is divided from the colony using a standard ventilation mesh, typically utilized in beekeeping applications, placed underneath the hot side heatsink. The access of bees to the area beneath the hive roof is thus blocked, as it would be in any conventional LR hive. The overall system is designed to be cost-effective and completely compatible with standard hive components, maximizing the ease of deployment and making it acceptable to a wide beekeeping community.

3. Experimental setup

3.1. Assessing the optimal load resistance

To simulate the load applied to the harvesting system, the optimal load resistance R_{L_max} needs to be determined for the tested prototype. This allows the calculation of the harvesters' power output from the experimentally assessed voltages. A suitable setup for the determination of R_{L_max}, shown in Figure 3, is therefore designed. As it can be seen in Figure 3a, it comprises two 12 V / 60 W ceramic heaters placed beneath the hot side heatsink of the harvesting system. In Figure 3b it is visible that the heaters are powered by a laboratory power supply (1) connected via a BTS7960 43A H-bridge (2), and controlled by using a National Instruments MyRIO-1900 I/O device (3) [10] via an appropriately configured virtual instrument (VI) running on a PC (4). Temperature sensors are placed on both heatsinks and the measured values T_{hot} and T_{cold} are used by the VI to maintain, via a PID controller, a constant temperature difference of ~ 4 °C. The ambient temperature in the laboratory, i.e., the cold side temperature (5), is controlled by an AC unit, simulating thus as closely as possible the environmental conditions of the device during in-situ testing which, however, considering the overall system setup, resulted in a rather small achievable temperature differential. In the conceived setup, the NI MyRIO device is used both as the control unit as well as the data acquisition (DAQ) and logging device. The measured data include the cold and hot side temperatures, i.e., the temperature difference, as well as the voltage generated by the two TEGs, which are connected to a variable resistance box (6) [11], enabling a smooth sweep through the selected range of resistances. The harvesters themselves are enclosed in the standard Langstroth top feeder (7), in the same way they would be placed in-situ on the actual hive and insulated in the same way from the environment. The thus assessed voltage values are used to calculate the power output at every considered load resistance value; the highest power output therefore corresponds to the optimal value R_{L_max} of the studied harvesting system.

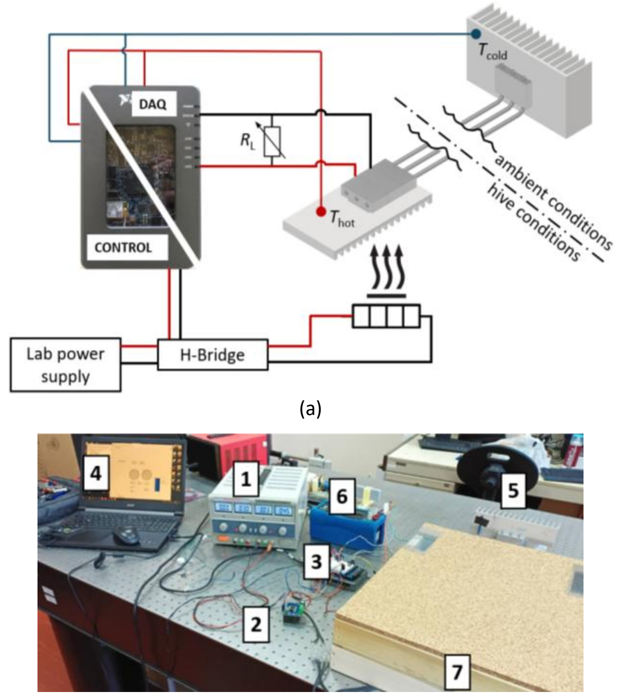


Figure 3. Schematic representation of the optimal resistance value assessment setup (a), and the actual experimental setup (b)

As depicted in Figure 4, the highest power output of the harvesting system (P_{max} ≈ 2.5 mW) is achieved at a load resistance value R_L = 12 Ω. As the optimal resistance values do not vary significantly vs. the temperature difference [12], this resistance value can be considered optimal for the proposed harvesting system configuration in the expected wide range of operating temperatures, and it will thus be used as the set value for the in-situ testing of the prototype system.

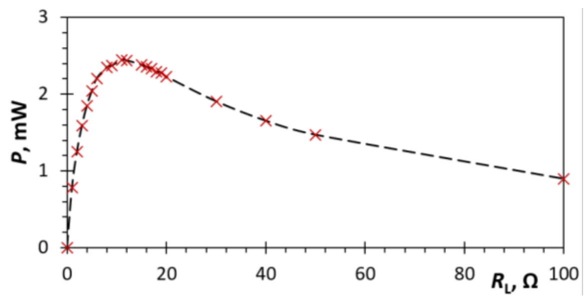
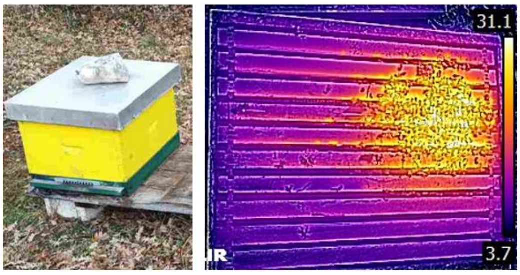


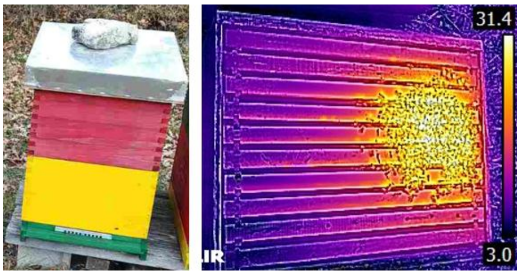
Figure 4. Power output of the energy harvesting system for varying load resistance values

3.2. In-situ prototype testing

To accurately estimate the performances of the proposed energy harvesting system, it needs to be tested in-situ on actual honeybee colonies. For this purpose, the experiments are conducted on hives located in the central area of the Croatian peninsula Istria. Two Carniolan honeybee (lat. *apis mellifera carnica*) colonies of different strength are therefore selected. In the weaker colony, displayed in Figure 5a, the cluster occupies only a single hive box, while in the stronger colony (shown in Figure 5b) most of the cluster is located in the lower box, with bees from its upper section reaching all the way to the top of the upper box. The location of the individual clusters is clearly visible in the adjacent thermograms, where the bees in both cases are roughly placed in the centre of the hive, shifted towards the front, corresponding, therefore, to the foreseen position of the hot side heatsink of the proposed energy harvesting system. The thermograms are obtained here by using a Flir® E6 Pro thermal imaging camera, with a resolution of 240 x 180 pixels, an accuracy of ± 2 % and a field of view of 33° x 25°, scrupulously calibrated, as certified by the manufacturer [13].



(a)



(b)

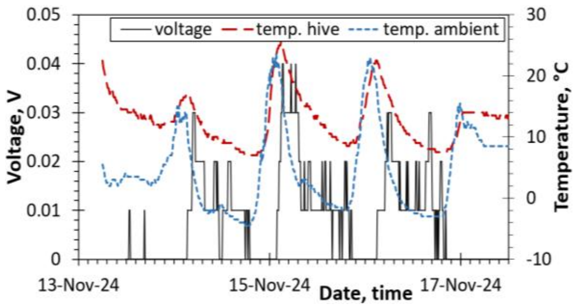
Figure 5. Hives with colonies of different strength: a weaker colony occupying a single box (a), and a stronger one occupying two boxes (b)

Figure 6. In-situ testing of the prototype energy harvesting system

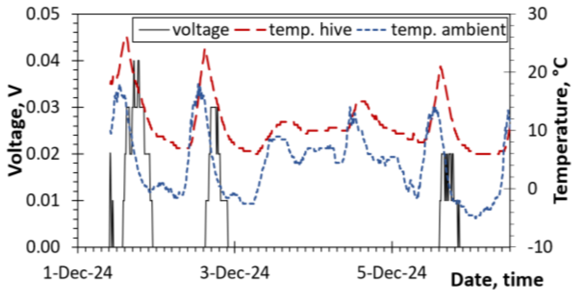
To assure a usable temperature gradient between the hive interior and the environment, measurements are performed in late fall, from mid-November to early December, with a R_{L_max} = 12 Ω resistor connected in parallel to the two TEGs. To facilitate in-situ data acquisition, two types of data logging devices are used. Two LASCAR® EasyLog EL-USB-2 temperature data loggers, with a resolution of 0.5 °C and an accuracy of 0.45 °C [14], are used to monitor the temperature inside and outside the hive near the heatsinks, while a Voltcraft® DL-250V DC voltage logger, with a resolution of 0.01 V and an accuracy of 0.5 % [15], is employed to measure the voltage generated by the conceived energy harvesting system. The hot side temperature logger is placed inside the hive between the top of the frames and the hot side heatsink, while the cold side one is positioned on the top of the hive roof, in a way that minimises its exposure to sunlight. The prototype of the harvesting system on the weaker colony is shown in Figure 6, with the outer heatsink and one of the temperature loggers clearly visible.

4. Results and discussion

As mentioned, the voltage generated by the energy harvesting system is measured using a Voltcraft® voltage logger, connected to the leads of the resistor simulating the electrical load (various possible sensors) applied to the TEGs. The hence measured voltage values are graphically displayed in Figure 7, together with the inner hive and the ambient temperature values. The results for the single and double box hive are shown in Figure 7a and 7b, respectively. It can thus be seen that, in accordance with the temperature difference between the hive interior and the environment, the generated voltage oscillates from zero to 0.04 V. The voltage data graph appears to be stepped, due to the typical low voltages generated by TEGs at smaller thermal gradients, combined with the measurement resolution of the voltage logger, limited to 0.01 V. The hive temperature clearly mirrors the oscillation of the ambient temperature, albeit with a slight time-shift and a reduced magnitude, periodically bringing the two values closer together. As visible in Figure 7b on December 4th, this minimization of the thermal differential induces a shift towards nil generated voltages.



(a)



(b)

Figure 7. Voltage generated by the harvesting system for varying temperature differences measured on a single (a), and a double box hive (b)

By comparing the results in Figures 7a and 7b, it can also be observed that the overall performances of the harvesting system in terms of peak voltages are not significantly affected by the strength of the colony. The results show, however, a difference in the inner temperatures between the two colonies, with the inner temperature coming much closer to the ambient one in the weaker colony compared to the stronger one. This difference would likely be observable also in terms of the generated voltage if a higher resolution voltage logger would have been used. When output power is considered, due to the fairly low generated voltage, the peak powers do not exceed 0.15 mW. However, as the overall system is devised to accumulate and store low-level harvested energy over a period of time, the individual peak powers are of lesser importance.

5. Energy storage

To utilize the low levels of harvested energy, a suitable energy storage solution, such as a supercapacitor, needs to be considered. As the voltage generated by TEGs is low, a step-up DC-DC converter is thus required to successfully charge a supercapacitor. In this frame, a MATRIX® Mercury Boost Converter, able to provide a voltage output of 4.2 V with a start-up voltage of only 24 mV [16], is employed. It is optimized for a 12 Ω impedance, thus matching the external resistance value.

To test the viability of this approach, an experimental setup, similar to the one described in Section 3, is devised, where an array of capacitors with increasing capacitance values from 1 F to 5 F is charged using the proposed energy harvesting system in laboratory conditions at an average temperature difference, limited by the laboratory conditions, of 5.6 °C. As it can be observed in Figure 8, two capacitors, namely the 1 F and the 2 F ones, have been successfully charged to over 80 % within a 6-hour period, while a longer time is needed for the larger capacitance units, so that up to 24 hours are required to charge a 5 F capacitor to a comparable level. It must be noted here, however, that the temperature oscillations present in the actual environment were not considered, which would imply longer charging times for in-situ applications.

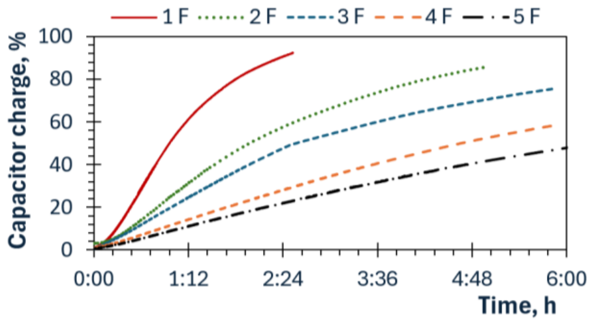


Figure 8. Supercapacitors charging times in laboratory conditions

These results show in any case the viability of the proposed approach, and the suitability of the developed energy storage setup for the foreseen application. Additionally, as it can be seen in Figure 7, the in -situ generated peak voltages commonly reach and exceed the start-up voltage of the step-up converter, facilitating thus a regular charging of the used supercapacitors.

6. Conclusions and outlook

A novel energy harvesting system, aimed at utilizing waste heat generated by honeybee colonies, is described in this work. The operational principles and the basic components are outlined. Two experimental setups, one aimed at assessing the optimal load resistance of the harvesting system, and the other developed for the in-situ tests, are therefore described in detail. The optimal value of the load resistance for the studied energy harvesting system configuration is determined experimentally in laboratory conditions. The characteristics of the measurement and logging equipment used for the in-situ tests are listed as well. The prototype of the energy harvesting system is therefore tested in-situ on two honeybee colonies of different strengths, and the resulting data is logged using dataloggers. The thus obtained results are graphically represented in terms of generated voltages and temperature differences over a period of time. The generated 0.04 V voltage peaks, obtained at an optimal load resistance value R_{L_max} = 12 Ω, correspond to the periods when the largest temperature differences occur, decreasing to zero when the ambient temperature approaches that inside the hive.

A suitable energy storage system, comprising of a step-up DC-DC voltage converter paired with a supercapacitor, is also considered. Several supercapacitors are tested in laboratory conditions, with resulting charging times (> 80 % charge) ranging from about 2 to 24 hours. It is important to note that, in general, the in-situ attained peak voltages exceed the start-up voltage of the considered step-up converter, allowing thus a regular charging of the supercapacitor. The proposed energy storage system needs, however, to be tested next on actual hives to properly validate its performances. Furthermore, future in-situ tests need to include additional environmental sensors, such as e.g. a lux sensor, to assess the insolation of the overall system, or an anemometer, to also investigate the effects of wind on the outer heatsink. Additionally, a more detailed thermal analysis of the heatsinks and heat pipes is required to improve the efficiency and the thermal balance the system with respect to the thermal energy generated by the colony. Additional system configurations, with different numbers of TEGs and their placement in the hives, need to be considered as well. A successful refinement of the proposed energy harvesting system in the outlined direction will enable the development of a fully functional autonomous hive monitoring system. Such a system needs to be studied over a longer period of time in diverse climates to assess its viability and scalability, as well as its potential impact on the colonies. As different honeybee species adapted to a variety of climates, a possible impact of specific species behaviour on the harvester operation should also be considered. The thus refined system should be able to operate in winter conditions and in remote locations, providing the beekeepers with a real-time insight into the state of the managed honeybee colonies in terms of strength, health, food stores etc. If the autonomous energy harvesting powered monitoring system is to be accessible to a wide range of beekeepers, a detailed life cycle assessment (LCA) will also have to be conducted, considering its overall carbon footprint. Such a system would be certainly beneficial to the beekeeping community by reducing the number of colonies succumbing to winter losses.

Acknowledgements

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