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Design and testing of an advanced honeybee waste heat-powered energy harvester

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Abstract

An overwintering honeybee colony maintains the hive inner temperature of up to 35 °C, creating a considerable temperature difference Δ*T* with respect to the low ambient temperatures. The resulting temperature gradient, induced by the metabolic waste heat typically lost through hive walls, can be efficiently exploited by using thermoelectric energy harvesting (EH) technologies, providing electrical energy for low power IoT-based autonomous hive monitoring systems. Based on a previously developed proof-of-concept harvester, an advanced setup, comprising six low Δ*T* thermoelectric generators (TEGs), two heatsinks connected by heat pipes, a step-up DC-DC converter, and a supercapacitor for energy storage, is developed and tested in laboratory conditions. A standard 5-frame Langstroth nucleus hive is used, while the temperature difference is controlled to simulate the conditions in actual hives. As the TEG-based transducing device is connected to the DC-DC converter with a pre-set range of input voltages, the interconnection of individual TEG modules needs to be carefully considered in terms of its effect on the capacitor's charging times, which should be minimized. The TEGs are thus tested while connected in series (6S), in parallel (6P), and, by using a combined approach, in a parallel connection of 3 assemblies of 2 serially connected TEGs (3P2S), and a parallel connection of 2 assemblies of 3 serially connected TEGs (2P3S). Based on the obtained results, the chosen configuration of the device is tested in-situ. An initial configuration of an IoT-based sensor node is also proposed. Different harvester device's constituting materials with better thermal properties will be considered next, and additional attention will be placed on the thermal interfaces between the key components.

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

1. Introduction

Effects of climate change, diseases, and human activity have led to issues in managed honeybee colonies, such as increased winter losses, thus reducing the numbers of these pollinators with a very important role in agriculture. Hive monitoring offers here a promising solution by enabling real-time assessment of colony conditions. An upgraded version of a previously proposed innovative energy harvesting (EH) concept [1], intended for battery-less (i.e., environmentally friendly) powering of an autonomous hive monitoring system, which can be aimed at swarm detection [2], measuring temperature [3] or other parameters such as sound, CO_2 percentage and weight [4], is presented in this work. The EH system is designed to collect waste (metabolic) heat generated by a honeybee colony [5] and convert it into usable electrical energy via thermoelectric generators (TEGs). In fact, to maintain the bee cluster temperature at levels of up to 35°C [6], as the colony overwinters, it generates a substantial amount of heat [7]. As shown in Figure 1, the new EH system comprises an assembly of six TEG modules (1), and two heat sinks – respectively for the hot (2) and the cold (3) side, mutually connected via two copper-methanol heat pipes (4). To increase heat conductivity, the heat sinks, as well as the hot (5) and cold side (6) interface blocks, are made of copper, while the methanol heat pipes ensure safe operation at sub-zero ambient temperatures. To minimize heat losses, all the exposed metal surfaces are, in turn, covered by a thermal insulating foam. Due to rather low output voltages typical for TEGs, a DC-DC converter (7) with ultra-low start-up voltage is then used to enable energy storage in a supercapacitor (8).

As multiple TEG modules are used, several connection configurations can be used, i.e., the TEGs can be connected in series (6S) and in parallel (6P), as well as via a parallel connection of 3 assemblies of 2 serially connected TEGs (3P2S), or a parallel connection of 2 assemblies of 3 serially connected TEGs (2P3S). This work presents an experimental study on how the different connections of the TEG modules influence the supercapacitor charging times in laboratory conditions. The new EH device is then tested in-situ using the most suitable TEGs' connection configuration, and the open-circuit voltage values are assessed. An overall autonomous IoT sensor node, comprising sensors and communication units coupled to the EH powering assembly, is also proposed, and the respective duty cycle is calculated.

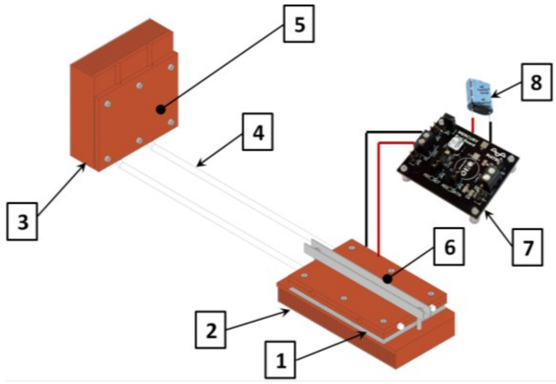


Figure 1. Thermoelectric energy harvester assembly aimed at the utilization of the waste heat of a honeybee colony

2. Connection configurations of multiple TEG modules

The behaviour of the TEG modules connected in series and in parallel, in terms of the respective voltage and current outputs, is fairly straightforward and well documented [8], while the somewhat more complex cases of combined connections have been experimentally studied only in recent literature [9]. However, due to the typical low output voltages of TEG modules, particularly at relatively low temperature differences in the foreseen operating conditions, as well as the pre-set operating parameters of the considered DC-DC converter, required to charge the supercapacitor, i.e., the minimum start-up voltage and an upper voltage limit, the connection method of the TEGs needs to be carefully considered. The respective study is performed by using an experimental setup comprising two ceramic heaters controlled via a virtual instrument (VI) running on a NI® MyRIO [10] device, thus simulating the heat generated by the honeybee colony. The setup is enclosed in a standard wooden 5-frame Langstroth nucleus hive together with the heaters, while the cold side heat sink is exposed to ambient air, kept at a constant temperature by employing an AC unit. The used TECTEG MFR.® TEG2-126LDT TEG modules [11] are connected to a Matrix® 411-MCRY DC-DC converter [12] with a U_{st} = 24 mV start-up voltage and a U_{lim} = 500 mV input voltage limit, which charges a U_{SC} = 5 V, C_{SC} = 0.5 F supercapacitor. The converter output voltage is U_{out} = 4.2 V, and this value is considered as the indication of a fully charged capacitor, as measured by the VI running on an NI® MyRIO device. A PCE Instruments® PCE-T 420 4-channel temperature data logger [13] is used to measure the temperature values in four different points, i.e., to monitor the ambient temperature and the air temperature within the hive, as well as the temperatures at both the hot and cold side heat sinks. In the used setup, the logger is interfaced to K-type thermocouples, and in the foreseen measurement range it has a measurement resolution of 0.1 °C, and an accuracy of ± 0.2 % of the measured value [13].

As schematically represented in Figure 2, the six used TEG modules are then connected in series (6S), in parallel (6P), in a parallel connection of 3 assemblies of 2 serially connected TEGs (3P2S), and a parallel connection of 2 assemblies of 3 serially connected TEGs (2P3S).

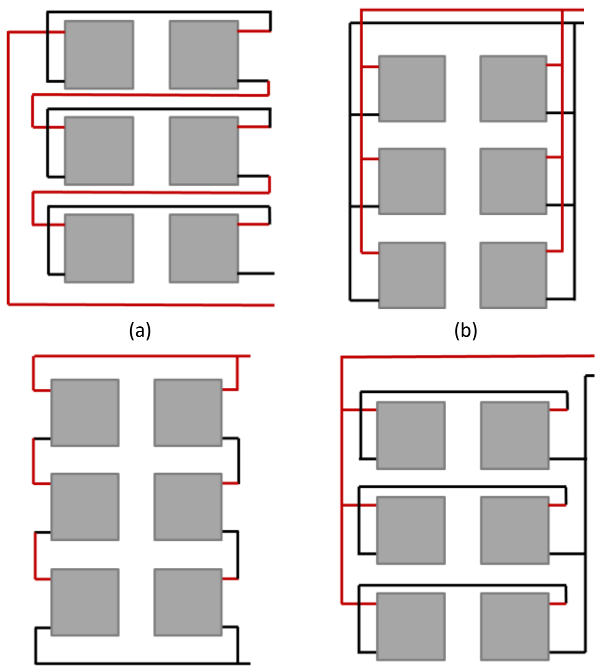


Figure 2. Schematic representation of the considered TEG connection configurations: 6S (a), 6P (b), 3S2P (c) and 2S3P (d)

The times required to achieve the complete charging of the supercapacitor are then measured for the different TEG configurations. The measurements are performed in steady-state conditions at comparable average temperature differences ΔT_{ave}, measured at the heat sinks, ranging from ΔT_{ave} = 16,1 °C for the 3S2P case, up to ΔT_{ave} = 21,8 °C for the 6P case. By maintaining the thermal conditions under control, as well as by keeping the measurements as short as possible, the average temperature differences measured during the experiments were kept within ± 5 % compared to those occurring in a honeybee colony. The significant variation in actual temperature values within an active hive is also taken into account.

The average temperature differences ΔT_{ave} and the respective charging times t_{ch} are listed in Table 1 and graphically displayed in Figure 3. Open circuit (OC) voltage measurements U_{OCave} are also carried out for the considered TEG configurations at average temperature differences $\Delta T_{ave} \approx 10$ °C, and the obtained results are shown in the lower part of Table 1.

Table 1. Charging times and OC voltages for the different TEG connection configurations

	Charging times			
	6S	**6P**	**2S3P**	**3S2P**
ΔT_{ave}/°C	21.8	16.9	15.7	16.1
t_{ch}/min	172.7	221.1	54.4	51.4
	Average OC voltages			
	6S	**6P**	**2S3P**	**3S2P**
ΔT_{ave}/°C	10.45	11.85	9.5	9.7
U_{OCave}/V	0.503	0.079	0.147	0.144

The results reported in Table 1 and Figure 3 indicate that the 6P configuration implies the longest times to fully charge the supercapacitor, with t_{ch} = 221.1 min, followed by the 6S configuration with t_{ch} = 172.7 min. These long charging times can be attributed to the impedance mismatch and the variation in the overall resistances. Also, in the 6S configuration the output voltages U_{OCave} are so high that they tend to become higher than the converter's upper limit. On the other hand, the combined configurations performed similarly, both requiring around t_{ch} = 50 min to fully charge the C_{SC} = 0.5 F capacitor. Since both configurations, when operating at the considered low temperature differences, nearly coincide in terms of the output voltages (Table 1) and currents, this seems quite reasonable [9]. In any case, the benefits of the combined assemblies can be clearly seen, as both the 2S3P and the 3S2P configuration are significantly better than the fully serial and parallel ones, with the 3S2P configuration resulting in slightly shorter charging times. The benefits are also evident in terms of the OC voltages U_{OCave}, where both the 6S and the 6P configurations induce issues with respect to the voltage input range of the converter, while the combined ones provide similar mid-range voltage values, well suited for the unpredictable temperature differences during real in-situ operation.

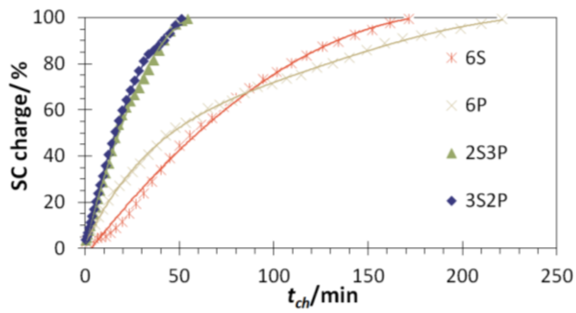
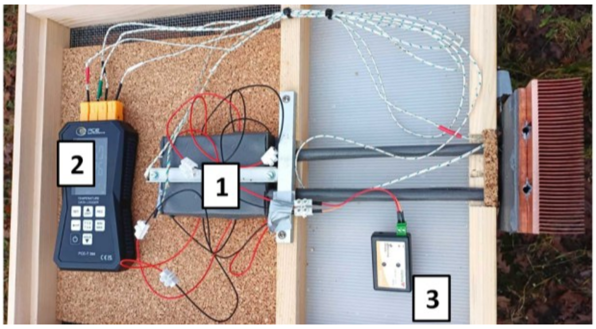


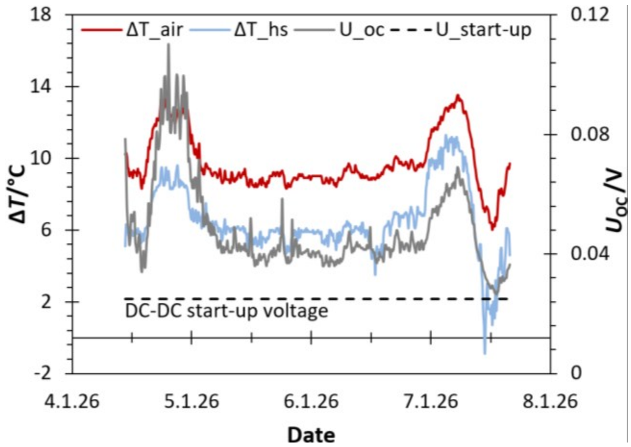
Figure 3. Supercapacitor charging times for the considered TEG connection configurations

3. In-situ testing

To assess the in-situ performances of the proposed EH system in real life conditions, a field test is carried out next. As displayed in Figure 4a, the six TEG modules are thus connected in a 3S2P configuration and the whole EH system (1) is integrated in a standard Langstroth hive containing an overwintering colony of Carniolan honeybees (lat. *apis mellifera carnica*). The aforementioned 4-channel temperature data logger (2) [13] is employed to keep track of the temperature values within the hive, the surrounding environment, and at both the hot and the cold side heat sinks. The temperature difference between the hive interior and the surrounding air ΔT_{air}, as well as that between the two heat sinks ΔT_{hs}, can hence be assessed. To measure the open circuit (OC) voltage output U_{OC} of the EH device without an attached electrical load, a MadgeTech® Volt101A voltage data logger (3), having a resolution of 0,5 mV and an accuracy of ± 0,016 V [14], is also used.



(a)



(b)

Figure 4. In-situ setup for testing the EH device in a Langstroth hive (a), and measured U_{OC} values at varying ΔT_{air} and ΔT_{hs} values (b)

The resulting OC voltages, generated by the harvester in real life conditions, are graphically displayed in Figure 4b, along with the aforementioned temperature differences ΔT_{air} and ΔT_{hs}. It can be observed that, due to convection at the heat sinks, there is an expected offset between the values of these temperature differences, ranging from 1.2 up to 7.8 °C. In terms of harvester's performances, the temperature difference between the heat sinks, averaging ΔT_{hs_ave} = 6.5 °C, is considered to be more important, as it is closer to the temperature difference between the hot and cold sides of the TEG modules. The output voltage follows, in turn, the variation in the temperature difference, averaging U_{OCave} = 0.048 V, and displaying maximum values of U_{OCmax} = 0,1 V. The minimum OC voltage values U_{OCmin} are larger than the lowest input voltage required by the considered DC-DC converter U_{st}; in fact, as it can be observed in Figure 4b, U_{OCmin} = 0.027 V, whereas U_{st} = 0.024 V. These results indicate, therefore, that the output OC voltage falls within the input limits of the considered DC-DC converter, thus proving the suitability of the selected TEG configuration 3S2P for the foreseen application.

4. IoT components and duty cycle

Based on previous considerations, i.e., colony waste heat EH viability [15] and colony strength assessment [16], the overall autonomous hive monitoring system should comprise several key ultra-low power IoT components, i.e., a microcontroller unit (MCU), A-D converters, communication modules (LoRa, NB-IoT, Space IoT, or alternatives [8]), as well as the foreseen sensors and the respective data logging and filtering components.

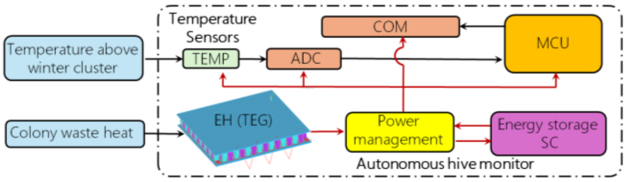


Figure 5. Schematic representation of the considered autonomous IoT sensor node aimed at hive monitoring [15]

The STMicroelectronics® STM32 Nucleo-64 board [17] represents herein the central element of the foreseen system, as it comprises an ultra-low power MCU, a Switched-Mode Power Supply (SMPS), A-D converters, a data storage module, and a communication module using the LoRa protocol. To measure the temperatures within the hive and assess the size and strength of the colony [16], several temperature sensors can then be employed; the Microchip Technology® MCP9700A-E/TO ultra-low power sensors are thus considered [18].

Based on the available data and technical specifications of the mentioned commercially available IoT components, i.e., the Nucleo-64 board manuals [17, 19], MCP9700A temperature sensor [18] and Semtech® LoRa transceiver [21] datasheets, the respective Semtech® LoRa calculator [22], as well as recent literature related to battery-less IoT systems [23], the power requirements of the considered components, their characteristic operational modes, and the corresponding cycles are estimated as listed in Table 2.

Table 2. Power requirements and cycle duration for the considered IoT components

Nucleo-WL55JC2 & MCP9700A-E/TO	
Power requirements	
Mode:	**Current/mA**
Wake MCU @ 48 MHz	3.46
Wake & read temp. sensor (per sensor)	0.015
Wake & read temp. sensor (for 11 sensors)	0.165
Transmit Tx 20 dB	107.1
Total active load (one sensor), I_{active}	110.6
Total active load (for 11 sensors), $I_{active11}$	110,7
Total sleep load, I_{sleep}	0.00107
Cycle duration	
Cycle:	**Time/s**
t_{cycle} = 24 h	86400
MCU wake-up & stabilize	0.02
MCP9700 power & read	0.005
Prepare data package	0.01
LoRaWAN transmission (one sensor)	1.81
LoRaWAN transmission (for 11 sensors)	2.8
Return to sleep	0.005
Total active time, $t_{active11}$	2.84
Total sleep time, $t_{sleep11}$ = t_{cycle} - $t_{active11}$	86397.16

From the listed data, the duty cycle D for 11 sensors is calculated as [24]:

$$D = \frac{t_{active11}}{t_{active11} + t_{sleep11}} \quad (1)$$

while the average load current I_{av} is determined as [24]:

$$I_{av} = I_{active11} \cdot D + I_{sleep} \cdot (1 - D) \quad (2)$$

The useful time of utilisation of the energy stored in the storage system (battery or supercapacitor) SC_{time} can, therefore, finally be assessed as [24]:

$$SC_{\text{time}} = \frac{SC_{\text{capacity}}\ (mAh)}{I_{\text{av}}\ (mA)} \tag{3}$$

For the autonomous sensor node configuration considered in this work, and comprising 11 MCP9700A-E/TO temperature sensors connected to a Nucleo-64 board, and a LoRa transceiver transmitting the collected data, the active current amounts therefore to $I_{\text{active11}} \approx 110.7$ mA. If such a system collects and transmits data once per day, the duty cycle is $D = 3.3\ 10^{-5}$, i.e., 0.0033 %. If the system is powered via the previously considered $C_{SC} = 0.5$ F supercapacitor charged to $U_{out} = 4.2$ V, resulting in $SC_{\text{capacity}} = 0.583$ mAh, the time during which the supercapacitor, even without any additional charging, could provide energy, would be $SC_{\text{time}} = 123.86$ h or 5.16 days. This goes to showing that, by carefully considering the periods of peak power consumption, the limited amount of collected and stored energy can be a trouble-free and very efficient solution for the herein considered autonomous sensor node application.

5. Conclusions and outlook

A new and improved honeybee colony waste heat energy harvester device, based on six TEG modules, is conceived and described in this work. Different TEG connection configurations are considered, i.e., a series (6S), a parallel (6P), and two configurations based on a combination of parallelly assembled sets of serially connected TEGs (3S2P and 2S3P). All the configurations are tested in laboratory conditions on a suitably devised experimental setup. The ability to fully charge a $C_{\text{SC}} = 0.5$ F supercapacitor is then assessed by using an apposite control and data acquisition system and a DC-DC converter, whose voltage limitations, when coupled to the different behaviour of the considered TEG configurations, play an important boundary condition. It could thus be shown that, in realistic low ΔT conditions, the combined configurations perform significantly better, fully charging the supercapacitor in around $t_{\text{ch}} \approx 50$ min. This can be attributed to the property of such configurations to perform between the two extreme cases of serial and parallel connections, providing thus sufficient voltage at low ΔT to start the converter, while keeping the current high enough to achieve manageable charging times.

To assess the performances of the harvester in real life conditions, the EH device, based on the TEG modules connected in the 3S2P configuration, is subsequently integrated into a standard wooden Langstroth hive occupied by a honeybee colony. The results of the field tests allowed confirming that the proposed approach enables providing voltage values appropriate to initiate and maintain the charging process of the supercapacitor. As the foreseen application is ultimately an autonomous hive monitoring system, essential ultra-low power IoT components, with their respective power requirements, are also considered. The key technical specification and operational cycles of the MCU, data storage, and LoRa communication transceiver modules, combined with temperature sensors, are therefore carefully analysed. The hence determined duty cycle and the resulting useful time of utilisation of the energy stored in the supercapacitor for the considered operating conditions, allowed clearly showing the viability of the proposed solutions.

In the prosecution of the work, the performances of the proposed harvester device will be tested in-situ also in terms of the supercapacitor charging times in various environmental conditions. Various harvester device's constituting materials with better thermal properties will also be considered, and additional attention will be placed on the thermal interfaces between the key components.

The full IoT sensor node will then be assembled and tested in laboratory conditions first, and then during the final field tests. A functional autonomous IoT sensor node aimed at honeybee colony monitoring, powered by the colony's waste heat and able to operate in remote locations during winter conditions, will therefore be obtained. Such a system will provide the beekeeping community with invaluable insights into the state of the overwintering colonies, as well as with an effective tool to prevent and mitigate the respective winter losses.

Acknowledgements

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